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Virtual Reality for the Assessment of Unilateral Spatial Neglect and the Therapy of Acrophobia

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Zusammenfassung

Anwendungen der virtuellen Realität (Virtual Reality, VR) finden bereits in vielen Bereichen, abseits von Unterhaltungszwecken, ihren Einsatz. So wurde das Potential auch im medizinischen Bereich früh erkannt und immer mehr medizinische Anwendungsszenarien werden durch die Nutzung von VR geschaffen. Diese VR Anwendungen bringen eine Vielzahl von Vorteilen gegenüber herkömmlicher medizinischer Anwendungen mit sich. So können Szenarien entworfen werden, die in der Realität nicht oder nur verbunden mit einem hohen Aufwand realisiert werden können. Das ermöglicht neue Therapie- und Rehabilitationsansätze und kann dabei gleichzeitig noch das medizinische Personal entlasten.

Besonders im Bereich der Therapie von mentalen Störungen wurde das Potential bereits frühzeitig erkannt. Auch für andere Bereiche, wie die kognitive und motorische Rehabilitation, werden immer neue Anwendungsszenarien entwickelt. Für viele dieser Bereiche konnten im Vergleich zu herkömmlichen Therapiemethoden bereits vergleichbare Ergebnisse erzielt werden. Hierbei spielen eine Vielzahl von Faktoren eine wichtige Rolle, um eine geeignete medizinische VR Anwendung zu entwickeln. So müssen Interaktionen und Fortbewegung in der virtuellen Welt häufig speziell auf die Nutzer- bzw. Patientengruppe ausgelegt werden, um eine Nutzung zu ermöglichen. Dabei müssen außerdem Aspekte wie die VR Krankheit und das Präsenzempfinden beachtet werden.

Daher beschäftigt sich diese Arbeit mit der Entwicklung zweier Therapiesysteme für unterschiedliche medizinische Anwendungsfelder. Zum einen wird eine Anwendung zur virtuellen Straßenüberquerung vorgestellt. Es wurden zwei Studien durchgeführt. In der ersten Studie wurden 60 gesunde Teilnehmer getestet, um die Schwierigkeitsfaktoren einer virtuellen Straßenüberquerungsaufgabe zu untersuchen. In der zweiten Studie wurden 18 Schlaganfallpatienten getestet, um zu untersuchen, ob sie an einem räumlichen Neglect leiden. Dabei wurden Unterschiede in mehreren Messwerten zwischen Schlaganfallpatienten mit und ohne räumlichem Neglect festgestellt. Außerdem wurden Benutzerfreundlichkeit, Anwesenheit, VR-Krankheit und die Schwierigkeitsfaktoren untersucht. Die zweite entwickelte Anwendung beschäftigt sich mit der Therapie von Höhenangst. Hierfür wurden Szenarien entwickelt die Höhenangst hervorrufen sollen und Motivationselemente entworfen, die dabei helfen sollen den Patienten über einen längeren Zeitraum für die Therapie zu motivieren.

Abstract

Virtual reality (VR) applications are already being used in many areas beyond entertainment purposes. Thus, the potential of VR was also recognized early in the medical field, and more and more medical application scenarios of VR are being developed. These VR applications bring a multitude of advantages compared to conventional medical applications. Thus, scenarios can be designed that cannot be realized in reality or are associated with a high effort. VR enables, for example, new therapy and rehabilitation approaches and can also relieve the medical staff.

Especially in the field of therapy of mental disorders, the potential has already been recognized early on. New application scenarios are also being developed for other areas, such as cognitive and motor rehabilitation. For many of these areas, comparable results have already been achieved compared to conventional therapy methods. Here, a variety of factors play an essential role in developing a suitable medical VR application. For example, interactions and locomotion in the virtual world need to be specifically designed for the user or patient group to support them. In addition, aspects such as VR Sickness and Sense of Presence must be considered.

Therefore, this thesis deals with the development of two therapy systems for different medical application fields. First, an application for virtual road crossing is presented. Two studies were conducted. In the first study 60 healthy participants were tested to investigate difficulty factors of a virtual road crossing task. In the second study, 18 stroke patients were tested to investigate if they suffer from spatial neglect. Here, differences in several measurements were found between stroke patients with and without spatial neglect. Usability, presence, VR sickness and the difficulty factors were also evaluated. The second developed application deals with the therapy of fear of heights. For this purpose, scenarios were developed to evoke fear of heights, and motivational elements were designed to help motivate the patient for the therapy over a longer period of time.

Contents

Acronyms

ADL Activities of Daily Living

ANOVA Analysis of Variance

CAVE Cave Automatic Virtual Environment

ET Exposure Therapy

FoV Field of View

HMD Head-Mounted Display

IPQ Igroup Presence Questionnaire

iVRoad immersive Virtual Road

PTSD Post-Traumatic Stress Disorder

SHT Standardized Head Turn

SSQ Simulator Sickness Questionnaire

USEQ User Satisfaction Evaluation Questionnaire

USN Unilateral Spatial Neglect

VE Virtual Environment

VR Virtual Reality

VRET Virtual Reality Exposure Therapy

1 Introduction

Virtual reality (VR) has experienced a significant boom in recent years due to the technical development of modern VR headsets. VR headsets became more affordable for a broader audience. Primarily, modern VR headsets were targeted at the consumer market for entertainment purposes. However, the potential of VR for a wide range of non-entertainment applications was also quickly recognized. For example, VR can be used as a medium in teaching [1, 2] and industrial design [3, 4]. Another vast and vital area is the use of VR in the medical field. Here, training applications for surgeons are developed and applied to train special procedures and operations [5, 6]. However, it is also an area with many possible applications and great potential [7, 8, 9] when applied to patients suffering from a wide variety of diseases and impairments. Patients can perform and train on various scenarios and tasks in a safe environment adapted to them [10]. In this thesis, applications for two medical use cases are presented.

The first VR application addresses the cognitive rehabilitation of stroke patients. Approximately 14 million people are suffering a stroke each year worldwide [11]. In the past, strokes mainly affected older people. In recent years, however, there has been a rapid increase in strokes among people under the age of 54 [12]. A large proportion of these stroke patients subsequently require professional medical care for many years, as strokes are the main reason for severe disabilities [13]. These disabilities have different characteristics (e.g. cognitive or motor impairments) and degrees of severity. Unilateral spatial neglect (USN) occurs especially frequently as a consequence of stroke. Patients suffering from USN no longer perceive one half of the world, so it highly affects their everyday lives. Conventional paper-and-pencil assessment tests are insufficient in diagnosing USN, especially in the chronic stage [14].

The second part of this thesis deals with the therapy of mental disorders, in particular the treatment of acrophobia (fear of heights). Jacobi et al. [15] report that 27.7 % of the German population suffer from some mental disorders once in their lives. For successful therapy, patients need to participate actively and face their problems over a longer period of time. The approach of exposure therapy (ET) is often used, where the patient is exposed to the stimuli that cause them anxiety. Using VR technology, this approach is called virtual reality exposure therapy (VRET). The applicability of VR in the therapy of mental disorders was discovered very early, and its effectiveness was shown [16].

1.1 Contributions

In this thesis, a VR application called iVRoad (**i**mmersive **V**irtual **Road**) was developed, in which stroke patients can perform virtual road crossings. The goal was to develop a VR tool to assess whether stroke patients suffer from USN. For this purpose, the ability of stroke patients to use a VR application to cross virtual roads must be tested. Therefore, special care must be taken to ensure that the application is easy to use. Subsequently, factors should be identified that could be used in the future to distinguish patients with and without USN. Here, especially activities of daily living (ADL) are suitable scenarios for virtual environments (VE) in VR. For this purpose, the first version of this application was developed to investigate difficulty factors in virtual road crossings, as this is important to adapt the task difficulty adequately in therapy and rehabilitation applications. A locomotion method that can be used for patients with different disabilities was designed and implemented. A study with 60 healthy subjects was conducted to evaluate the difficulty factors. The knowledge gained could then be used in the further development of the application. A new VE was designed to meet the defined requirements for use with stroke patients to detect USN. Therefore, various visual and auditory distractors were integrated into the VE, since focusing on a specific task is particularly difficult for patients with USN. The application was evaluated with 18 stroke patients. It was investigated whether stroke patients are able to use the VR application independently and without the occurrence of side effects. In addition, parameters that can be used to distinguish stroke patients with and without USN were evaluated.

In addition to the VR application for cognitive rehabilitation, this thesis also presents a VRET application to treat acrophobia. The goal was to create scenarios that induce fear of heights and are easily adaptable. Aspects to motivate the patient and assist the therapist should also be considered. Two exposure scenarios were designed to induce fear of heights in patients. The application was designed to have a set of parameters which the therapist can adjust before the start of therapy to adjust the difficulty level of the application. Also presented is an anxiety reporting system that allows automatic recording of patient-reported anxiety levels during therapy. Two motivational elements have been integrated into the VE to increase the patient's motivation and reduce the likelihood of quitting the therapy. Finally, evaluation recommendations are given for this application as to which questions can be investigated.

The thesis focuses on three research questions:

RQ1: What are suitable *Difficulty Factors* in VR rehabilitation and therapy applications?

RQ2: Which measurements during a VR road crossing task could be used to distinguish between stroke patients with and without USN?

RQ3: Are stroke patients able to use a VR road crossing tasks independently and without the occurrence of side effects?

1.2 Structure

The thesis is divided into the following chapters:

- **Chapter 2** – This chapter presents the medical and technical background of this thesis. In the medical background, the general topic of strokes and the rehabilitation process are discussed first. Afterwards, associated impairments and in particular USN are introduced. In the following step, anxiety disorders, their types and triggers are presented, and therapy approaches are shown. The technical background focuses on the topic of VR. VR headsets and their specifications are presented, interaction and locomotion types in VR are introduced, and the terms *VR Sickness*, *Immersion* and *Presence*, which are essential in the field of VR, are defined and explained.

- **Chapter 3** – The third chapter deals with related work on the topic of cognitive rehabilitation and therapy of mental disorders using VR applications. The advantages and disadvantages of using VR as a rehabilitation and therapy application are explained and discussed using a wide range of examples. In addition, the

SWOT analysis conducted by Rizzo and Kim [17] in 2005 on VR rehabilitation and therapy is discussed in the context of the related work presented.

- **Chapter 4** – This chapter presents a VR application for virtual road crossing. This application is designed to be performed by stroke patients. For this purpose, related work from traffic psychology on a virtual road crossing, and virtual road crossing in stroke patients is presented. Then, the development of the first application is presented, where the goal was to identify *Difficulty Factors* for crossing virtual roads. These findings were subsequently used to develop and evaluate the VR assessment application for stroke patients.

- **Chapter 5** – In the fifth chapter, a VRET application is introduced, which is designed to be applied to the therapy of patients with acrophobia. For this purpose, the interviews conducted with experienced therapists and the requirements derived are presented. Since no study has been conducted with the application so far, potential directions for studies are described and discussed.

- **Chapter 6** – The last chapter concludes with a summary of the most important findings and contributions of the thesis. Furthermore, possibilities for future work are presented.

2 Background

This section gives a small insight into the most important medical backgrounds. First, strokes and their consequences and impairments are discussed. Since this work also deals with the treatment of anxiety, the causes, types, and existing therapeutic approaches for anxiety are also introduced in the following. In addition to the medical background, the second part of this chapter focuses on VR. Different VR headsets and possible input devices are introduced. Furthermore, topics such as locomotion in VR, *VR Sickness* and *Presence* will be discussed in more detail, as these are central elements for virtual reality and the experience of virtual worlds.

2.1 Medical Background

2.1.1 Stroke

Strokes are one of the leading causes of death and impairments [18]. It can be differed between ischemic and hemorrhagic stroke. A blockade of the blood flow typically causes ischemic strokes. The main reason for hemorrhagic strokes is the rupture of an aneurysm, where blood flows directly in the head, which leads to high intracranial pressure. Both types of stroke lead to brain regions no longer operating correctly [19]. The resulting shortage of oxygen and nutrients causes areas of the brain to die. The main reasons or factors that increase the probability of suffering a stroke are high blood pressure, smoking, less physical activity and diabetes [12, 20]. After a stroke has occurred, it is extremely important that the affected brain regions are quickly resupplied with blood, any open bleeding is stopped and the brain pressure is reduced. The longer the brain regions are undersupplied, the more irreversibly these brain regions are damaged.

Stroke Rehabilitation After the initial treatment of the patient, it is very important to start early with a comprehensive diagnosis to be able to perform first specific trainings. The affected brain regions should be stimulated again as early as possible to increase the chances of regaining abilities. Due to the plasticity of the brain, in particular young patients are usually in a better starting position to achieve better recovery of their abilities [21].

Cognitive Impairments after Stroke

The potential impairments after a stroke are extremely varied and depend on the affected brain regions. The impairments can range from visual defects, motor disabilities, memory or attention problems [19]. As this thesis is focusing on USN, this syndrome is described in detail in the following. *Hemianopia* is also mentioned concisely because the symptoms of these two impairments can be very similar at first view.

Unilateral Spatial Neglect Neglect is a supramodal syndrome frequently occurring after unilateral brain damage and is primarily associated with stroke. USN is more severe and persistent following right hemisphere brain damage. In the acute phase of stroke, reports on frequency vary between 50-80 % [22, 23]. Neglect is primarily a disorder of attention where patients cannot report or respond to stimuli on their contralesional side. This leads to severe difficulties in managing everyday life, e.g. patients often collide with objects, such as door frames, on their affected side or have problems while reading texts. Another typical characteristic is the pathological failure or unawareness to recognize the cognitive impairment associated with a circumscribed brain damage (*anosognosia*) [24]. Sometimes patients even did not recognize that they have a second arm and wonder which person this arm belongs to [19]. In patients with *anosognosia* it is therefore essential to start there and try to make the patient aware of their impairments [24].

First indications of a USN are recognized by doctors early on through behavioral and gaze observations. If a patient reacts very rarely and unreliably to stimuli on one side, this is a strong indicator for a present neglect. Simple paper-and-pencil tests are used to verify these indications [24]. The most important ones are the *visual search task* [25] and the *line bisection test* [26]. **Figure 2.1** shows typical examples of drawings from right hemisphere USN patients. Especially the left sides of the images are drawn partially incomplete or distorted, which is a typical sign for USN. In the *visual search task*, the patient should mark certain stimuli in a presented set of stimuli. It can be observed that the patient usually omits stimuli on the contralateral side. In the line bisection test, horizontal lines in the subjective center should be crossed out. Patients with right hemisphere USN tend to cross lines further to the right (see **Figure 2.1E**) and completely ignore lines in the left area. In neglect patients, a shift of the subjective center into the ipsilateral half of the body can be observed. In contrast, patients with hemianopia typically overcompensate and their subjective center lies further within their restricted range. Therefore, this test is beneficial for differential diagnosis in the acute stage after stroke [24].

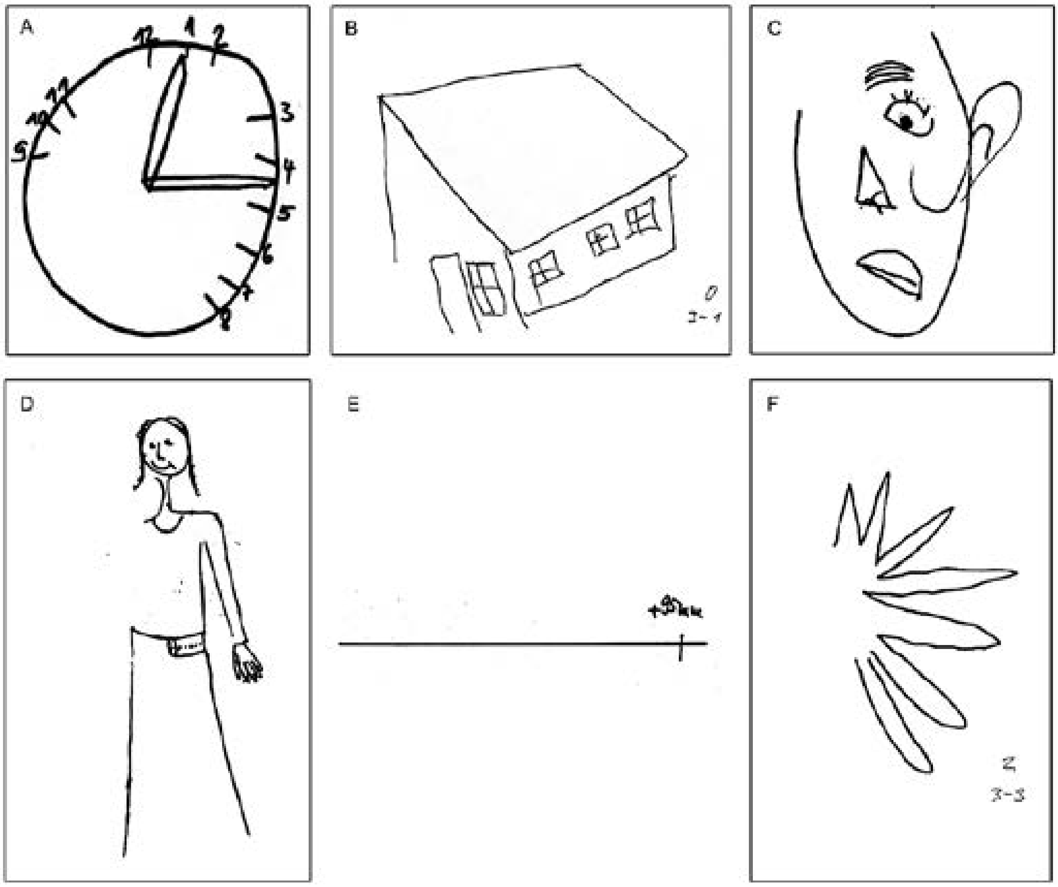
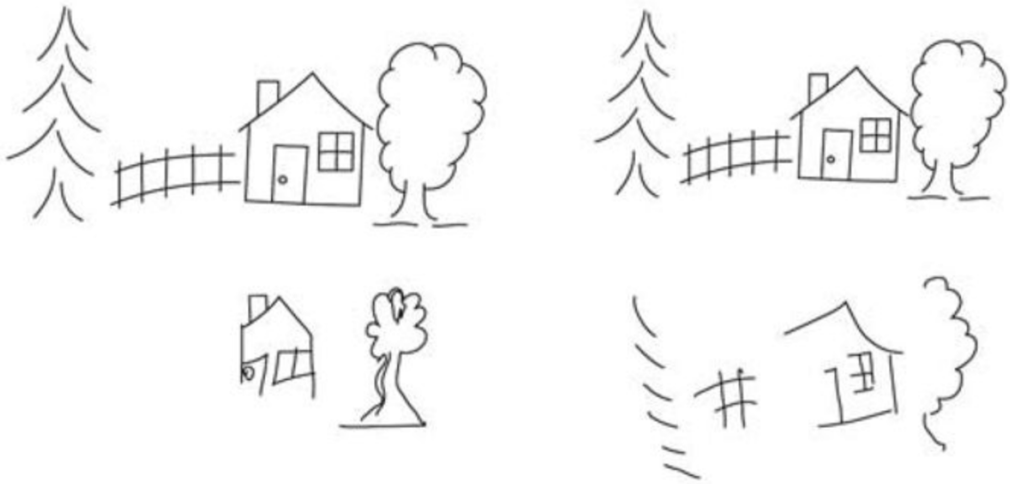


Figure 2.1: Example drawings of neglect patients. Notable are the omissions on the left side of the drawings and the typical shift of the crossed line to the right side. Image from Kalmbach et al. [27] © 2018 Kaden-Verlag.



(a) Egocentric neglect (b) Allocentric neglect

Figure 2.2: Illustration of a patient with an egocentric (left) and an allocentric (right) neglect. Image from Kortte and Hillis [28] © 2009 Springer Nature.

USN can be divided into two types:

- Egocentric neglect: Based on the position of the patient, objects and stimuli on the left side are neglected (see **Figure 2.2a**).
- Allocentric neglect: Regardless of the patient's position, the left side of each object is neglected (see **Figure 2.2b**).

USN can manifest in patients in different areas or distances from their own bodies, also called space-related neglect (see **Figure 2.3**) [23, 24]:

- Personal space: Neglect of areas on the own body.
- Peripersonal space: Neglect of objects within arm's reach.
- Extrapersonal space: Neglect of objects beyond arm's reach.

In the field of neglect research, it has been criticized for a long time that too little research of transferability into patients' activities of everyday life has been conducted [29]. Furthermore, conventional assessment methods lack sensitivity as they contain mainly non-functional tasks performed in peripersonal space, using static, two-dimensional methods [30]. Especially in the chronic phase, conventional paper-and-pencil tasks

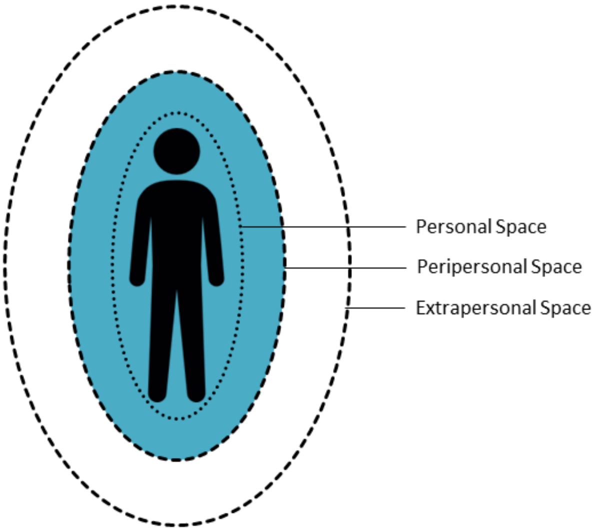


Figure 2.3: Illustration of personal, peripersonal and extrapersonal space.

might lack detecting USN symptoms [14]. A typical compensation technique to improve the possibility of reading a text for neglect patients is to draw a vertical line in front of the first word in each row and tell the patient to start reading each row after they find the vertical line. Otherwise, patients often start reading in the middle of a row and have problems understanding the text.

Hemianopia The symptoms of hemianopia initially look very similar to the symptoms of USN, but the disorder only refers to the sense of sight. In hemianopia, the vision is disturbed on one side of the visual field. In contrast to USN, however, patients are still aware of the existence of both sides of the world [31]. Therefore, in patients with hemianopia, it is not necessary to first address the unawareness, as is the case with neglect patients. Instead, it can directly be started to train compensation techniques and cope with their impairment. For the diagnosis, the patient's visual field is recorded. The patient is supposed to look at a fixed point in the center and react to any stimuli that appear in the environment without averting their gaze from the center. In this way, the patient's visual field can be gradually recorded. In the end, one has an evaluation of the areas in which the patient can see and those where they cannot. Computer-assisted programs are very suitable for this purpose, as the scanning of the entire visual field can be automated.

Phases of Neurological Rehabilitation in Germany

The Neurological Rehabilitation Working Group of the Association of German Pension Insurance Institutions developed a phase model for neurological rehabilitation in 1995 [32]. This model consists of six phases (A-F) [32, 33].

- Phase A – Acute treatment: Stabilization of the patient in the acute phase after, for example, suffering a stroke.
- Phase B – Early rehabilitation: Intensive action and rehabilitation with a medical and therapeutic focus.
- Phase C – Continuing rehabilitation: The focus is on restoring the patient's independence.
- Phase D – Follow-up rehabilitation: Reduction of existing disabilities.
- Phase E – Follow-up care and vocational rehabilitation: Transition from medical rehabilitation back to employability.
- Phase F – Activating, condition-maintaining long-term care in case of persistent high need of care: Patients who - after intensive rehabilitation - still have severe impairments, so that permanent care is necessary.

Not every patient goes through all model phases; instead, every patient is being assigned to the appropriate phase depending on the severity and progression of rehabilitation. Thus, it is possible to approximately infer their current condition from the current rehabilitation phase that a patient is in.

2.1.2 Anxiety Disorders

Besides strokes, this work also addresses *mental disorders*, specifically *anxiety disorders*. Jacobi et al. [15] report that 27.7 % of the German population suffer from some kind of mental disorders once in their lives. There are large differences between different groups (e.g. gender, age, social status). For example, more women (33.3 %) than men (22 %) are affected by mental disorders. Occurring mental disorders are eating disorders, affective disorders (e.g. depression), obsessive-compulsive disorders and anxiety disorders. Especially anxiety disorders take a very large part. Thus, 15.3 %, which means 9.8 million people, suffer from some kind of anxiety disorders. But what are fear and anxiety anyway and what are anxiety disorders?

Fear and Anxiety *Fear* and *anxiety* are basic human emotions and a normal part of our lives, even if in different degrees. Both terms are often used together and interchangeable. However, experts define both terms differently. Fear is a normal stress reaction and protects us in everyday situations. Fear is usually caused by known and well-defined threats, such as an assault, where the attacker is the threat [34, 35].

In anxiety, on the other hand, the threats tend to be undefined. *Anxiety* may occur, for example, when walking alone down a dark street. In this case, there is no direct threat, but many people feel unsafe in such a situation because they imagine sudden dangerous events [35]. Threats do not only have to be physical but can also occur on a mental level.

Anxiety and Fear-Related Disorders It is important to differentiate between anxiety and anxiety disorders. People with anxiety disorder have developed a high sensitivity to certain stimuli. Thus, even thoughts of the situation/stimulus cause anxiety. This can increase to such an extent that affected people try to avoid these stimuli and situations completely. If affected people get into situations where this is not possible, they experience severe stress [36]. In such situations, individuals tend to distract themselves from the anxiety with other things or to suppress it. This behavior can become so internalized that it is performed quite automatically [37]. Even though many people suffer from only a mild form of anxiety disorder, it can still manifest and lead to severe consequences for the normal performance of everyday life [16]. The literature reports that less than 20 % of affected people seek help, even though therapy offers great chances of success [38, 39]. Often, affected people think they can manage the symptoms themselves or have resigned themselves to living with them. Often, there is also a lack of information about where to get help. However, social and financial aspects also play a role. Affected individuals do not want to be seen as “sick” and are concerned about what their personal surroundings might think if they enter therapy [40]. The goal of therapy is often to make people aware that the situations that cause anxiety are harmless and that no negative consequences should be expected. Common symptoms of anxiety disorders are sleep problems, restlessness, concentration problems, nausea, dizziness and many others [41].

Types of Anxiety and Fear-Related Disorders

In the International Classification of Diseases (ICD-11) of the World Health Organization anxiety and fear-related disorders are divided into seven categories [42, 43]:

- Generalized anxiety disorder
- Panic disorder
- Agoraphobia
- Specific phobia
- Social anxiety disorder
- Separation anxiety disorder
- Selective mutism

Generalized anxiety disorder describes anxiety symptoms and excessive apprehension that are present for several months. These usually relate to specific areas of life, such as family, finances and the workplace, and can severely impact the lives of affected people [43].

The term *panic disorder* is used when people experience recurrent panic attacks independent of situations or stimuli. During panic attacks, intense fear and anxiety occur within a short period of time, accompanied by various symptoms (e.g. sweating, increased heart rate, dizziness) [43].

In *agoraphobia*, the affected individuals are afraid of situations from which they cannot easily escape or from which it is difficult to get help, e.g. within crowds, elevators, or on long-distance travels. However, this should not be mixed up with claustrophobia, in which narrow places trigger the fear.

In *specific phobias*, the trigger of fear is directed against a particular stimulus or situation. *Arachnophobia* (fear of spiders) and *acrophobia* (fear of heights) are among the most widespread *specific phobias* [44].

With *social anxiety disorder*, affected individuals are afraid of being the center of attention or acting embarrassingly. This includes speaking in front of people, but also conversations with previously unknown people. They fear rejection and therefore often avoid social gatherings or appropriate situations [45]. This can lead to complete social isolation, which can have a large influence on everyday life.

When people have severe problems with being temporarily separated from any close attachment figures, this is referred to as *separation anxiety disorder*. In case of children, this can be the parents, so that the child does not want to go to school, or in case of adults, it can be the romantic partner [43].

Selective mutism is expressed when people show language problems depending on the situation they find themselves in. For example, it is often observed that children do not have problems expressing themselves at home, but they do at school [43].

Causes of Anxiety Disorders

The causes of anxiety disorders are as varied as their types and characteristics. The reasons are often divided into three categories [41, 46, 47]:

- *Biological causes*: heredity, illness, medications, nutritional factors
- *Psychological causes*: personality traits, low self-esteem, cognitive dissonance, negative emotions, development crises
- *Social causes*: adverse life experiences, lack of social support, work stress, lack of social skills, natural calamities

Therapy Approaches

There are many different approaches to anxiety disorder therapy. Depending on the type of disorder, the appropriate approach is selected. Two types are presented below and one approach is discussed in more detail.

One commonly used type of therapy is *Cognitive Behavioral Therapy* [48]. Here, the therapy goal is to replace negative thinking and ineffective behavior patterns with more realistic thoughts. They learn that no harmful consequences are to be expected from the anxiety-inducing stimuli. This approach is pervasive with social phobias.

Exposure therapy (ET) is often considered the most effective type of therapy for anxiety disorders [35, 49]. The goal of this therapy approach is to confront the affected person with situations that cause them anxiety in a safe environment. Meanwhile, the therapist helps them to deal with the situation and to stay calm. In addition, the therapist gives tips on how to handle such situations in the future. However, the affected persons must face their *anxieties*. This is the only way to overcome the avoidance and safety behaviors. Over time, patients become more comfortable and regain control of their fear perception. However, not every patient benefits from ET (non-responder rates vary between 10 and 30 %) [50]. There are also reports on the return of anxiety after the treatment [51].

A variation of the ET is the *Imaginal Exposure Therapy*. It is often a compromise if exposure in the real world is not possible or only with difficulties. However, the results are also often weaker and very dependent on the imagination of the affected person.

Virtual Reality Exposure Therapy (VRET) can potentially combine the benefits of both approaches. Albert "Skip" Rizzo did pioneer work on VRET, especially for patients with *Post-Traumatic Stress Disorder* (PTSD). VRET applications can improve the accessibility of ET for affected people. With this, transferring the mechanisms of real-life ET is essential to create an effective application [52]. This is a great strength of VRET because any real situation can be simulated. However, these can also be extended by elements that would not be feasible in the real world. For example, scenarios such as a flight in an airplane can be completed virtually. People with a fear of flying are otherwise often difficult to treat with ET because the effort required for exposure is extremely high [53]. Motivation is an essential factor for successful therapy. Even if patients are motivated, it requires a considerable amount of effort by a skilled behavioral therapist to successfully treat the disorder. A main challenge for a behavioral therapist using ET is to motivate patients to attend therapy regularly. The use of VRET also offers the possibility of treating patients with less effort and, thus, more cost-effectively since no travel time to the corresponding locations is necessary. Therefore, the entry barrier for the beginning of a therapy is also reduced. Examples of VRET applications are presented in Section 3.2.

2.2 Technical Background

The following section will first define the term VR in general. Since this work focuses on using VR headsets as an output device for the VE, different VR headsets will be introduced and all the following topics also refer to VR headsets. Other modalities like CAVEs (Cave Automatic Virtual Environment) are not part of this thesis; therefore, they will only be briefly discussed, especially in Chapter 3, when related work is presented. Possibilities to interact and locomote in VE with VR headsets are described. *VR Sickness*, as a common problem of immersive VR, and possibilities to reduce this side effect will be introduced. At the end of this chapter, the terms *Immersion* and *Presence* will be described, as they are essential factors for the experience of VE.

Virtual Reality VR aims to present a virtual world to the user and make them feel like they are in this virtual world. Cruz-Neira [54] came up with one of many different definitions for VR in 1993: "Virtual Reality refers to immersive, interactive, multi-sensory, viewer-centered, required to build these environments." VR headsets are used for this purpose, providing the user with an image from an egocentric perspective. In doing so, the user is presented with a slightly offset image on both eyes, creating a stereo effect. VR headsets visually isolate the user entirely from their surroundings. However, for a user to feel immersed in the world, both the technology and the software have to accomplish certain aspects. How much *Presence* a user feels when using VR also depends on the individual user (more on *Immersion* and *Presence* in Section 2.2.5). The application of VR ranges on a spectrum. Thus, 360-degree videos can be viewed, which have no interaction other than looking around, but still put the user in the corresponding situation of the video. This reaches up to highly interactive applications for entertainment, but also, e.g., training. VR offers the possibility of conveying realistic situations but can also draw on elements that would be difficult or impossible to achieve in reality.

2.2.1 VR Headsets

With the development of modern VR headsets (also often called Head-Mounted Display (HMD)) and the technical progress in computer graphics since 2012 through the Oculus Rift, there was a new boom for VR. There were already VR applications in the past, but due to hardware limitations, only very simple environments were possible. Thus, the first VR headsets were custom-made primarily since the necessary hardware was hardly available at that time. The technical specifications of the VR headsets were

(a) Oculus Rift

(b) HTC Vive

Figure 2.4: Images of the first two modern VR headsets. Image (a) from [55] and (b) from [56].

also very limited. The first two modern VR headsets were the Oculus Rift[1] and the HTC Vive[2]. At this point, VR headsets became affordable and applicable to a broad audience for the first time. In the meantime, many other companies launched their own VR headsets, e.g. Valve Index[3] and HP Reverb G2[4]. Modern VR headsets offer good screen resolutions, high refresh rates and a relatively large field of view (FoV), which are the apparent characteristics of VR headsets. Ergonomic aspects also become more and more important. Since the eye distance varies greatly among people, most modern VR headsets offer the possibility to adjust the distance of the lenses. The eye distance, head shapes and sizes vary among people. Therefore, most modern VR headsets have the option to adjust the head mount and the distance of the lenses. The weight of the VR headset also has an important impact on the wearing comfort, especially when wearing the headset over a longer time period.

In addition to these features, however, the type of tracking also plays a major role. There are two types of tracking [57]: outside-in and inside-out tracking. With outside-in tracking, external trackers are used to localize the VR headset and the controllers in the room, while with inside-out tracking the VR headset can determine its position in the room itself. This is how outside-in tracking was used with the first Oculus Rift, in which the VR headset was captured by several cameras that had to be distributed in the room. With the HTC Vive, on the other hand, the headset could determine

[1] https://www.oculus.com/rift, last accessed: May 2021
[2] https://www.vive.com/uk/, last accessed: May 2021
[3] https://www.valvesoftware.com/en/index, last accessed: May 2021
[4] https://www8.hp.com/us/en/vr/reverb-g2-vr-headset.html, last accessed: May 2021

its own position. However, this required the so-called lighthouses that emit light, and the VR headset can determine its position by detecting the light. This is also called marker-based inside-out tracking. Markerless inside-out tracking is used with more and more new VR headsets. No external technology is required for tracking. The VR headset has integrated sensors that can independently determine the position of the VR headset. Examples of VR headsets that use this technology are the Oculus Rift S[5] and the Windows Mixed Reality headsets[6]. These headsets offer the advantage that no external installations are necessary and therefore the quick use in new places is faster and easier.

VR headsets are also available with and without a cable connection. The first modern VR headsets always required a wired connection to a powerful PC. This has also made it difficult to deploy VR headsets in new places quickly. Many of the new VR headsets (e.g. Oculus Quest) rely on the standalone approach. This means that no external PC is required for use, which greatly improves mobility. However, these VR headsets are also not as powerful as the VR headsets with an external PC, which is at the expense of the graphical possibilities. There are also wireless solutions that make the cable connection to a PC no longer necessary.

There is also the possibility to experience simple VR applications and 360-degree videos with the smartphone. For this, the smartphone is attached to a holder to act as the screen of the VR headset. However, there is no tracking in the room. The integrated gyroscope of the smartphone is used to track the orientation and, therefore, the viewing direction. Eye-tracking is also a handy feature of VR headsets. It not only allows analyzing exactly where the user is looking during use, but it can also reduce the required computing time. Through the so-called *foveated rendering*, only the areas of the VE that the user is actively looking at are rendered with high quality. All other areas in the peripheral field of view are then rendered with lower quality, which is, however, not at all or hardly noticeable by the user. This can save a considerable amount of computing power [58]. There are already VR headsets with built-in eye trackers available (e.g. HTC Vive Pro Eye[7]), but also eye tracker add-ons are available.

Borrego et al. [59] made a comparison between Oculus Rift and HTC Vive on their application potential in the health care sector. Based on the tracking techniques, the

[5]https://www.oculus.com/rift-s/, last accessed: May 2021
[6]https://www.microsoft.com/en-us/mixed-reality/windows-mixed-reality, last accessed: May 2021
[7]https://www.vive.com/uk/product/vive-pro-eye/overview/, last accessed: May 2021

(a) HTC Vive Pro Controller

(b) Oculus Rift S Controller

Figure 2.5: Images of the VR controller of the HTC Vive Pro and Oculus Rift S. Image (b) from [61].

HTC Vive offers a much larger play area. Both devices offer excellent and comparable performance in seat height. When standing, the accuracy of the HTC Vive is a bit lower but still very accurate. They confirm that due to the high accuracy and the size of the play area both devices are very well suited for medical applications.

Examples of VR Headsets **Table 2.1** shows the specifications of some selected modern VR headsets released between 2012 and 2021. The Valve Index headset is particularly noteworthy, as it has a significantly larger FoV than the other example VR headsets. However, this is still significantly lower than the healthy horizontal FoV of the human eye of 180 degrees [60]. This reduced FoV is especially noticeable in applications where peripheral perception is important. The resolution of the displays is also improving, which is an important factor since the screens are so close to the eye. Here, the screendoor effect is often noticeable, which reduces the quality of the overall image. Thus, the VR headsets of the coming years will probably be able to produce ever higher resolution images, with an increasingly larger FoV.

2.2.2 Interaction in VR

There are several ways to interact with objects in VR. The most common way to interact is the use of a controller. The VR controller of the *Oculus Rift* and *HTC Vive* (see **Figure 2.5**) are tracked in the same way as the VR headsets, therefore, the controller can be localized in 3D space. These VR controllers offer joysticks/buttons/touchpads which enable the possibility to map various functionalities on them.

Table 2.1: Specifications of several modern VR headsets released between 2012 and 2021.

	Oculus Rift DK1	HTC Vive	HTC Vive Pro Eye	Oculus Quest	Valve Index	HP Reverb G2
Release year	2012	2016	2019	2019	2019	2021
Resolution per eye in pixel	1280×800	1080×1200	1440×1600	1440×1600	1440×1600	2160×2160
Field of view in degree	$\sim$100	$\sim$110	$\sim$110	$\sim$100	$\sim$130	$\sim$114
Refresh rate in Hz	60	90	90	72	80-144	90
Weight in gram	380	555	555	571	809	500
Standalone system	No	No	No	Yes	No	No
Tracking method	outside-in	marker-based inside out	marker-based inside-out	markerless inside-out	marker-based inside out	inside-out

Figure 2.6: Leap Motion mounted on a HTC Vive. Image from [62].

Often, also "normal" controllers of video consoles like *Microsoft Xbox* or *Sony Playstation* can be used, but do not offer a direct interaction since they cannot be localized in 3D space. The most natural way for humans to interact with objects is to use their bare hands. Optical input devices like the *Leap Motion Controller* or data gloves like the *Manus VR* glove can be used for this kind of interaction. The position of the hand in the room is recorded and thus enables interaction through gestures. The Leap Motion Controller can either be placed e.g., on a table, but then only the hands can be tracked if the user is interacting directly above them. Another possibility is to mount the Leap Motion Controller on the VR headsets (see **Figure 2.6**) so that the hands in front of the VR headset can be tracked.

This turns out to be difficult and unnatural in VR, because the virtual objects are not real and therefore do not provide haptic feedback. Data gloves try to reproduce the feeling of touching objects with the help of tactile feedback (e.g. via vibration). However, the technology is not yet mature and serves as an indicator that an object is touched, but gives no natural feeling for the object. This offers a high potential for even more immersive VR experiences.

2.2.3 Locomotion Techniques

In addition to interacting with objects, locomotion in the VE is also an important aspect. The most natural variant for locomotion is the direct translation of real locomotion in physical space into virtual space. Both the Oculus Rift and the HTC Vive allow real movement in the *play area*. The play area is defined during the configuration of the VR system and can be adapted to the conditions of the environment in which the

VR system will be used. This space is limited by technical constraints (cables, tracking area). Therefore, although real movement is possible to a certain extent, especially with smaller VE, for the exploration of large VE enhancements or other techniques are necessary [63]. The most obvious way is the control with the help of a controller (via joystick or control pad), as it is known from conventional video games. This does not result in any spatial restrictions in exploration. However, this can quickly lead to *VR Sickness*. *VR Sickness* is discussed in more detail in Section 2.2.4.

In the following, several examples of locomotion techniques are given, which were specifically developed for VR:

- Teleportation
- Walking-in-place/treadmill usage
- Redirected walking

Teleportation The user teleports from point to point in the VE. These points can be chosen freely, or only predefined positions can be used (see Figure 2 in the work of Bozgeyikli et al. [64]). This limits the exploration of the user, but the user's exploration can be directed in a targeted way [64]. However, the instantaneous movements can cause orientation difficulties for the user. Bozgeyikli et al. [64] have argued that this can happen, especially in very complex virtual worlds, when the user's viewing perspective changes significantly as a result of teleportation. This effect can be lowered by shortly fading the display while relocating the user.

Walking-in-Place The user walks on the spot in the real world. This is then interpreted as going forward in the VE. This can be achieved by oscillating movements with the controllers or via motion sensors on the user's body [65]. An alternative to walking-in-place is the use of a treadmill for locomotion in VE [66] (see **Figure 2.7**).

Redirected Walking Redirected walking successfully reduces the necessary physical real space while performing real walking to move in the VE. This is achieved with the help of different approaches. The basic idea is to rotate the virtual position as unnoticed as possible so that the user does not reach the edge of their play area, since the user performs body turns in the real world (see **Figure 2.8**). These are caused by

Figure 2.7: Image of a commercial omni-directional treadmill developed for VR. Image from Omni One by Virtuix [67].

the unnoticed rotation in the VE. One approach is to perform rotations in the VE to get the user to compensate this rotation in the real world. This leads to a more curved path [68]. A second approach is to exploit the change blindness while performing an eye blink. This short time period (blink duration varying between 100 to 400 ms) is used to perform rotations of the view in the VE [69]. More locomotion variants are discussed in the literature review of Cherni et al. [70].

2.2.4 VR Sickness

One of the main problems that occurs when using VR is *VR Sickness* (often also called cybersickness). The exact cause for the occurrence of *VR Sickness* has not yet been found. It is assumed to be a multifactorial problem. The most commonly used explanation is that when the visual stimuli received by the eye register a supposed movement, while the other senses, such as the vestibular sense, do not perceive this movement, *VR Sickness* occurs [57]. The review by Rebenitsch and Owen [72] describes that the incidence of *VR Sickness* varies greatly. In the considered studies, the frequency of *VR Sickness* varies between 30 [73] and 80 % [74]. Typical symptoms of *VR Sickness* are e.g. nausea, cold sweats, dizziness, headache and fatigue [75]. To measure *VR Sickness*, questionnaires are usually used, which are primarily aimed at assessing the occurring symptoms. Therefore, the Simulator Sickness Questionnaire (SSQ) [76] is

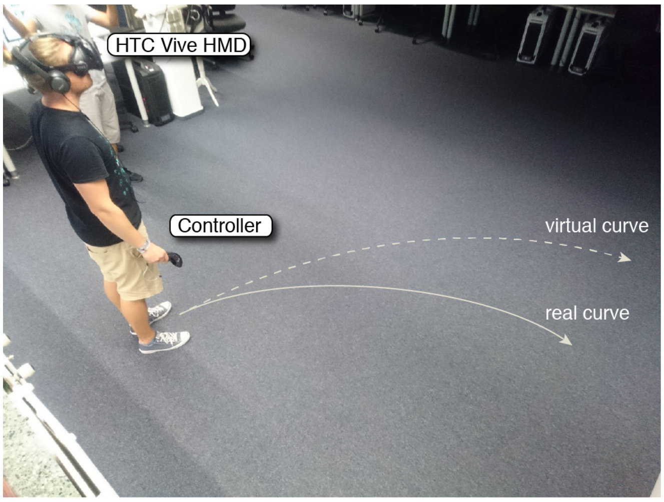


Figure 2.8: Illustration of the real and virtual path by using redirected walking. Image from Langbehn et al. [71] © 2017 IEEE.

often used. This questionnaire was designed for simulator sickness, but the symptoms are very similar to *VR Sickness*. In their book, Dörner et al. [57] report three major factors responsible for the occurrence of *VR Sickness*:

- The User
- The VR System
- The Application

The User The individual user is a crucial factor for the occurrence of *VR Sickness*, and at the same time the factor over which VR system and application developers have the least influence. Users who are also sensitive to motion sickness (e.g. seasickness) are also particularly susceptible to *VR Sickness*. Hence, there seems to be a connection. Children under the age of 12 have the highest susceptibility to motion sickness [77]. This decreases with increasing age, so that older people tend to be less susceptible to *VR Sickness*. However, there are also gender-specific differences [78]. Women have a larger FoV and are therefore more sensitive to screen flickering, which in turn results in greater susceptibility to motion sickness [57].

The VR System Looking at the specifications of VR systems, some conditions also bear a higher risk of *VR Sickness*. The applications should optimally run with less than 20ms per frame and in no case with more than 40 ms; otherwise, it can very fast cause *VR Sickness* [57]. Sufficiently strong hardware is necessary for this, but performance must also be considered when developing VR applications. In addition, tracking errors and a large FoV can promote the occurrence of *VR Sickness*. Studies could show that a reduced FoV (dynamic reduction) can reduce the potential for *VR Sickness* to occur [72, 79, 80].

The Application The nature and implementation of a VR application also have a major impact on the potential to induce *VR Sickness*. Dörner et al. [57] present a set of questions that should be asked when trying to predict how high the potential of an application is to cause *VR Sickness*. The more of these questions can be affirmed, the higher the *VR Sickness* potential. The questions refer to how the application is designed. Some sample questions:

- "Does the user spend a longer time in the application?"
- "Is the user rotated?"
- "Does the user have to move their head frequently?"
- "Are unusual movements performed?"

Interested readers can find the complete list in the book by Dörner et al. [57]. This offers insights into the future potential for causing *VR Sickness* in users and thus degrading the user experience, even at the conceptual design stage of an application.

2.2.5 Immersion & Presence

Immersion and *Presence* are two terms that come up quickly when working with VR. Both terms are often used interchangeably, but they deal with different aspects. There are many definitions for the two terms. In this thesis the definition of Slater and Wilbur [81] will be used. They define *Immersion* as an objective measure, describing the technology used and how well that technology is able to present the virtual world to create a high potential for *Sense of Presence*.

Presence, on the other hand, is a subjective measure generated by the interaction between the system and the user's perception. Users who feel immersed in the virtual world, as if they were actually there, experience a particularly high *Sense of Presence*. However, this state is not achieved by all users. The level of experience can have a major influence on the *Sense of Presence*. Inexperienced users can have more problems with the interaction with the system, which may hinder to develop a high *Sense of Presence*. However, the opposite can also occur. In particular experienced users, who have to pay less attention to interaction, pay more attention to the VE and may find inconsistencies and differences to the real world, which in turn could reduce their *Sense of Presence* [82]. Questionnaires are usually used to record the *Sense of Presence*. For example, there is the Presence Questionnaire [83], the iGroup Presence Questionnaire (IPQ) [84], and the Slater-Usoh-Steed Questionnaire [85]. However, *Sense of Presence* can also be measured using physiological data [86].

The Immersive Tendencies Questionnaire by Wittmer and Singer [83] is often used to measure how susceptible users are to *Immersion* in other situations. For example, how users can immerse themselves in plots of movies or books, or whether they frequently lose track of time. These are indicators of how much the person can also feel immersed in virtual worlds. Therefore, the questionnaire can be used before conducting a study in order to draw conclusions later on whether persons who showed a very low *Sense of Presence*, if any, are not as sensitive to it. Thus, it can be distinguished whether a possible *Presence* variability in the population of a study is due to the system or rather due to the users themselves. Presence perception is also negatively related to *VR Sickness* [87]. If a system induces a high level of *VR Sickness* in the user, then the user will not be able to engage with the world particularly well. Therefore, it is even more important to minimize the potential for *VR Sickness* to occur, as it can have a direct impact on the *Sense of Presence*. As described in Section 2.2.1, especially in the early days modern VR headsets were operated via cable connection to a PC. It could be assumed that this would be perceived as disturbing by the user and thus reduce the *Sense of Presence*. However, Gonçalves et al. [88] could not find any evidence for this in their study.

3 Related Work on Virtual Reality Rehabilitation and Therapy

VR applications offer the possibility to represent real environments and to extend them by virtual elements, which would not be feasible in reality or only with limitations. Thereby, the effort and costs for the preparation and implementation of therapy can be reduced [89]. VR applications can also lead to an increased motivation and active participation in therapy for patients. Both aspects are essential for a successful rehabilitation [90].

This chapter gives an overview of the current state of VR research in cognitive rehabilitation and therapy of mental disorders (especially anxiety disorders). The section on cognitive rehabilitation is divided into two parts, the general cognitive impairment and the USN. Especially the section on the USN is particularly relevant for the later content of this thesis. In the case of mental disorders, three specific phobias, fear of heights, fear of flying and fear of spiders, are discussed in more detail. These are followed by some selected examples of other mental disorders. In addition, a short overview of other types of therapy, where the use of VR is also promising, is given. The focus is mainly on VR work that has used a VR headset. In some areas, however, systems that use a desktop PC or a CAVE are also presented for supplementation or to provide a better understanding. In 2005, Rizzo and Kim [17] published a SWOT analysis for VR rehabilitation and therapy. A SWOT analysis is a tool for strategy planning and analyzes strengths (S), weaknesses (W), opportunities (O) and threats (T) of a certain topic, e.g. in the planning of a project or a thematic orientation of a company. See Figure 1 in the work of Rizzo and Kim [17] for the aspects highlighted by them. At the end of this chapter, some of these aspects will be discussed in more detail, based on developments in recent years. Finally, connections and differences between the different types of therapy are discussed.

3.1 Cognitive Rehabilitation

In the *early days* of VR therapy, the focus was on *motor rehabilitation* [90, 91, 92, 93]. There is an indication of an increase in motivation in the exercise of motor rehabilitation tasks when using a VR headset. For example, Hamzeheinejad et al. [94] showed this in combination with a cross trainer to support the user to navigate in varying virtual worlds. On a screen, the user could see themselves and had to perform real movements in order to react to stimuli on the screen. Commercial entertainment systems like Sony EyeToy, Nintendo Wii and Microsoft Kinect were used [95, 96, 97, 98].

However, the potential of VR for *cognitive rehabilitation* was also recognized early on [99, 100]. Computer-assisted rehabilitation may improve the cognitive performance, as various studies have shown [101, 102, 103, 104, 105]. Especially the potential of rehabilitation with the help of simulations and computer games that address ADLs is very high [103, 106, 107]. Therefore, the integration of ADL into VR came into the focus of research [104, 105, 108, 109]. Since this work is limited to the treatment of cognitive and psychological deficits, research dealing with motor rehabilitation is mostly not considered in detail.

The cognitive deficits, after e.g., a stroke or traumatic brain injury can be very diverse. Thus, the therapeutic approaches are designed for specific deficits. Studies suggest that VR used for rehabilitation may have a positive impact to restore attention, memory and spatial orientation [106, 110].

3.1.1 Cognitive Impairments

One of the first studies on the treatment of patients with brain damage with VR headsets was by Christiansen et al. [111] in 1998. At that time, VR was still in its early stages and the possibilities were very limited. Nevertheless, they created a realistic virtual kitchen scene in which the user's task was to successfully prepare a meal (see **Figure 3.1**). To interact with the environment, the users used a conventional computer mouse. The preparation of the meal was divided into 30 steps, and for each step there were points depending on performance. If the user had problems with individual steps of the preparation, hints, such as visual cues, were provided. After five errors within a preparation step, the step was skipped. With this work, the potential for mapping

Figure 3.1: Screenshot of the kitchen scene developed by Christiansen et al. [111] to treat patients with brain damage. Image from Christiansen et al. [111] © 1998 Elsevier.

real scenarios was recognized early on, even though the technical possibilities for the VE and interaction in the VE were still very much limited at that time.

Gamito et al. [112] (with VR headset) and Faria et al. [113] (desktop-based) developed systems in which everyday tasks were integrated into a *virtual city*. Patients had to navigate to specific locations in the virtual cities and complete various tasks there. In the study by Gamito et al. [112] the tasks mainly addressed attention and memory. These two areas were also addressed by Faria et al. [113], but in addition, they also addressed visual-spatial skills and executive functions. In both studies the subjects' abilities improved significantly more than in the control groups. A comparison between desktop-based VR and using a VR headset has not yet been made in this context. Cho et al. [114] developed a system for the treatment of attention deficits in children and adolescents with Attention Deficit Hyperactivity Disorder. They compared three groups (VR (N = 8), desktop-based VR (N = 9) and control group without training (N = 9)). Both the VR and desktop-based VR groups improved significantly compared to the pre- and post-tests. The VR group also scored better than the desktop-based VR group, but this difference was not significant. Nevertheless, the subjects found the VR application more exciting and motivating than the desktop-based application.

Belger et al. [115] transferred a desktop-based spatial memory training (VMT by Koenig

(a) Shopping shelves (b) Cash register

Figure 3.2: Mondelini et al. [118] developed a virtual supermarket as a cognitive rehabilitation training using the HTC Vive. (a) shows the shopping shelves with products and the shopping cart, and (b) shows the cash register with the products and the amount to be paid. Image (a) and (b) from Mondelini et al. [118] © 2019 Springer Nature.

et al. [116]) into a VR application using the Oculus Rift. Here, the participant is in front of a virtual table and has to remember a number of everyday objects and their position and then reproduce them. The patient can directly interact with his or her own hands in VR using the Leap Motion Controller[1]. This can lead to an increased *Sense of Presence*.

Mondellini et al. [117, 118] developed a system for training post-stroke patients, in which the patients perform a virtual shopping in a supermarket. They used the HTC Vive and the shopping process consisted of two phases. First, the right objects had to be put into the shopping cart. The users were able to move freely within the tracking area of 3x4 meters. Then, the payment process at the checkout was simulated. They evaluated their system in two iterations with healthy participants with regard to usability, presence and *VR Sickness*. Due to the high degree of realism (see **Figure 3.2**), some participants complained when some objects did not behave as in the real world or were accurately mapped (uncanny valley effect [119]). No side effects of the VR experience were stated by the participants. In the second iteration, they simplified the control of the system so that the same entries could be made with both controllers. This is especially important during the training of patients with, e.g., paralysis, who may only be able to use one hand. Already in 2008, Kang et al. [108] also developed a virtual shopping system, but the VR technology often caused negative side effects on the participants.

[1] https://www.ultraleap.com/product/leap-motion-controller/, last accessed: May 2021

In research, home therapy has also become more and more important in order to relieve the workload of medical staff, but at the same time to provide patients with an adequate therapy. Especially mobile VR headset solutions using the smartphone offer a particularly large potential in this regard, since many people already have a smartphone and thus the hardware is often already available and hardly any further costs are involved. A system presented by Varela et al. [120] addresses the short-term memory by solving mazes with an increasing difficulty using a mobile VR headset. In the higher levels of difficulty, in addition to navigating through the maze, various objects along the way must be counted. So far, an evaluation of this system has only taken place in the form of a case study with one participant for usability using the *System Usability Scale* [121]. In the case study, the usability was evaluated as very good, however, especially in the area of the users' feeling of security there is a great potential for improvement. Participants sometimes felt unsafe to use the system, mainly due to the VR headset isolating them from the real world.

3.1.2 Assessment and Training of Unilateral Spatial Neglect

In the following, some applications for the assessment and/or training of USN (recall Section 2.1.1) are presented. While, most of the relevant USN symptoms in the acute phase can be detected by conventional paper-and-pencil tests, these tests cannot detect all USN symptoms in the chronic neglect phase, because the patient has already learned various compensation techniques that hide symptoms or may have become accustomed to certain tests [14, 122]. A review confirms the great potential of VR in the assessment and training of patients with USN. VR systems offer great advantages in everyday use compared to conventional paper-and-pencil tests [123]. USN symptoms can become particularly visible in everyday situations, where a wide variety of stimuli and influences often affect patients. These can often not be perceived and processed completely or only very slowly [122, 124, 125].

Already in 2004, Kim et al. [126] developed an application for the assessment of visual neglect by using a VR headset. The task was quite simple. The user had to find a flying ball and follow it by moving their head (see Figure 3B in the work of Kim et al. [126]). Especially the scanning time, the number of cues and the error rate showed significant differences between the neglect patients and the healthy control subjects. Jannink et al. [127] developed a very similar system located at a virtual bus stop (see **Figure 3.3**).

However, this setting had no relation to the actual task and was only intended to strengthen the real relationship. Gradually, flying balls appeared in the environment, which flew towards the user. Various levels of difficulty were implemented. The level of difficulty determined from which direction and at which angle to the initial viewing direction the balls flew towards the user. The user had to look at the approaching ball and simultaneously press a button. This made the ball disappear and the next ball could spawn. They found differences in the task completion time and reaction time to balls on the left side. Both environments show the potential for detecting neglect using VR. The systems of Kim et al. [126] and Jannink et al. [127] are classic examples for the extension of a real VR scene by virtual elements that would not be possible in the real world.

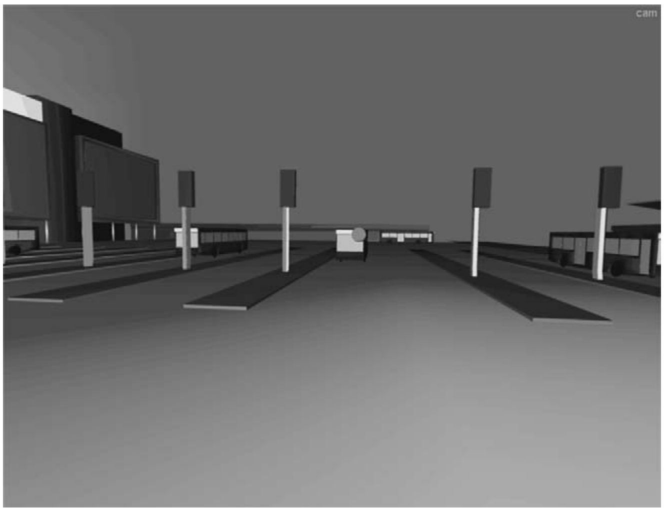


Figure 3.3: The VE used by Jannink et al. [127]. The task was to detect several flying balls that are approaching the user and react to them. Image from Jannink et al. [127] © 2009 Lippincott Williams & Wilkins.

Kim et al. [128, 129] developed a system where an avatar has to be protected from approaching vehicles. The idea is based on a road crossing task at a crosswalk. Vehicles approach from either the right or the left side at different speeds and the user has to signal with a mouse click when they have noticed an approaching vehicle (see Figure 5 in the work of Kim et al. [128]). Visual and auditory cues are used to facilitate perception. These cues are automatically activated if the participant does not react for too long. When comparing neglect patients and healthy control subjects, significant differences were found, especially in the reaction time to stimuli on the contralateral side.

Yasuda et al. [130] developed a visual search task for training personal and extrapersonal neglect. The first task was to touch virtual objects on a table (peripersonal neglect) from right to left and in the second task to name objects on a wall 15 meters away (extrapersonal neglect). For touching the objects on the table the users could use their own arm, since it was tracked by a Leap Motion Controller. A moving slit was used to support the training by directing the patients' attention to the restricted side. Although the entire environment was realistically implemented, it was also kept visually quite simple and limited to the stimuli relevant to the training (see **Figure 3.4**). In a small pilot study with ten USN patients, the possibility of improving extrapersonal neglect through VR training was shown. No positive influence was determined for peripersonal neglect. This indicates a beneficial impact of USN treatment using VR. However, further studies with suitable control groups are required.

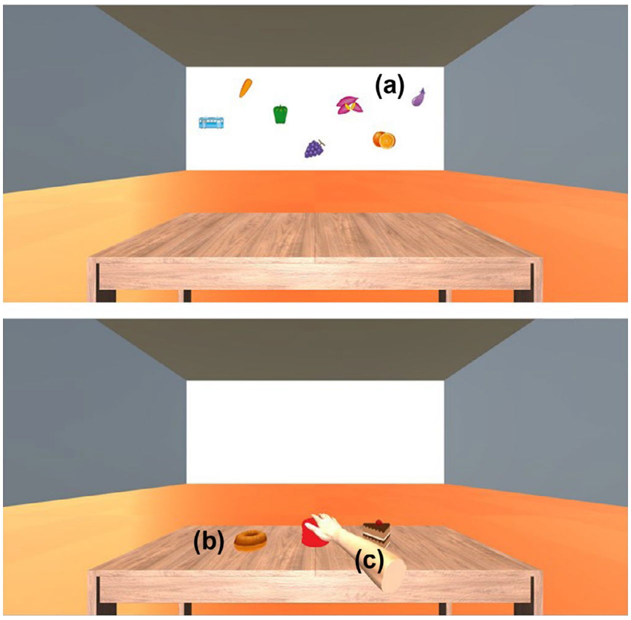


Figure 3.4: The VE from Yasuda et al. [130]. (a) shows the visual stimuli of the visual searching for extrapersonal space; (b) shows the virtual objects for the reaching task; and (c) shows the user's arm in the VE tracked by a Leap Motion Controller. Image from Yasuda et al. [130] © 2017 Taylor & Francis.

Transfer of Paper-and-Pencil Tasks in VR Classical paper-and-pencil tasks can also be realized in VR. The very common cancelation task [131, 132], which is used to find and mark certain stimuli in a large set of deflection stimuli, has been transferred to a VR application by Knobel et al. [133] (see **Figure 3.5**). The usability was rated as very good by both stroke patients and healthy control subjects. No side effects were observed. The results achieved were comparable to those of the conventional paper-and-pencil version. In future studies, any advantages over the paper-and-pencil variant would have to be investigated in more detail.

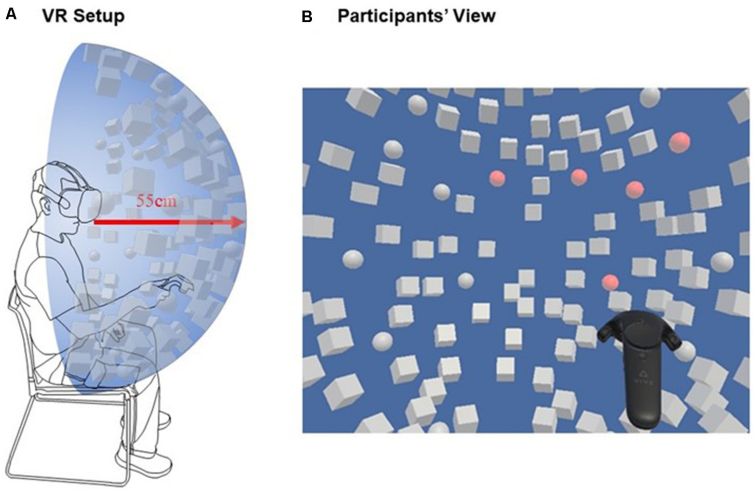


Figure 3.5: Setup and the user's view in the VR cancelation task developed by Knobel et al. [133]. Image from Knobel et al. [133] © 2020 Knobel, Kaufmann, Gerber, Cazzoli, Müri, Nyffeler and Nef.

Similarly, Ogurtsova et al. [134] transformed a cancelation task into an everyday task. One of the user's tasks is to discover a specific product on a shopping shelf with various products. In the second task, the user is supposed to navigate to the corresponding place on the shelf using a joystick. The VR headset used does not have headtracking, so the view onto the shopping shelf is static. Particularly in the complex scene, differences were found between the neglect patients and the healthy control subjects - reaction time, mediolateral deviations from the ideal path and longer navigation time.

3.2 Virtual Reality Expsosure Therapy

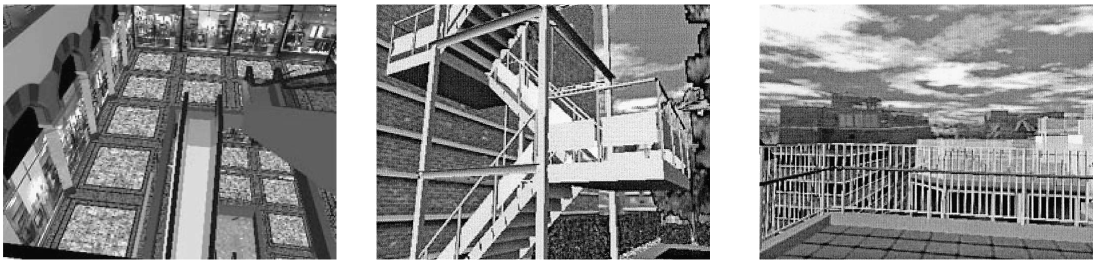
In ET, patients are repeatedly confronted with situations that are difficult for them or cause anxiety (recall Section 2.1.2). Already in the 1990s the potential of VR for the therapy of anxiety disorders was recognized and the first applications were developed [16]. VRET uses the advantages of VR to support ET. Mostly real situations are simulated virtually and often extended by additional virtual elements, which are hardly or not feasible in the real world. Their effectiveness and applicability has already been shown in a number of studies [135, 136, 137, 138]. Since the focus of this thesis is on the use of VR headsets, only applications that use a VR headset will be presented. In the following, VRET applications for the treatment of the three specific anxiety disorders acrophobia, fear of flying and arachnophobia are presented. These anxiety disorders are widespread and were already addressed in the early days of VRET development [139, 140, 141] and work is continuing on them. In addition to these three specific anxiety disorders, other systems are presented which deal with the treatment of agarophobia and social anxiety disorders. For more information, especially for other anxiety disorders, see Serrano et al. [142] and Freeman et al. [143]. The work of Serrano et al. [142] is part of a book that was recently released by Bouchard and Rizzo [144], which gives a great overview on psychological and neurocognitive interventions.

3.2.1 Fear of Heights

Hodges et al. [139] made the first attempt of virtual simulation for the generation and treatment of acrophobia with VR in 1995. For their system they aimed for at least 10 frames per second. In today's VR applications developers want to achieve at least 90 frames per second. With this goal they experimented how many details they could display with the technology of that time. This resulted in two possibilities. They could either choose a stereoscopic representation and integrate only a few details or a monoscopic representation with a higher degree of detail. Due to the technical limitations and the blurring of the stereoscopic representation, a monoscopic representation was chosen. The VE consisted of three scenarios that were supposed to simulate real situations. The three scenarios showed an open elevator, balconies or virtual bridges. For safety and haptic feedback, there was a platform with railings for the user to hold on to. The user held a tracker in their hand, which made it possible to display a virtual hand in VR. This enabled the interaction in the VE. The balconies and bridges were located at different heights. During exposure, the users were asked to report their current anxiety level every five minutes. Over a period of seven weeks, 17 subjects with tendencies to acrophobia completed a session of 35-45 minutes each week. The study showed that it was possible to induce acrophobia in the users with the help of the VE. The subjects showed a number of symptoms that are often associated with anxiety. The authors also emphasize the importance of creating a high degree of presence among users. There was a significant difference in anxiety-related measures between the treatment group and the control group [139].

Comparison of ET and VRET Emmelkamp et al. [145] used a similar system to investigate the difference between conventional ET and VRET. The system consisted of two scenarios; a water pool with a diving platform and a tower with a glass elevator (see Figure 1 in the work of Schuemie et al. [146]). As VR headset the Virtual-IO was used, which however has a very limited FoV. Since the headset was open at the bottom, a cloth was attached in front of the users' face in order to cover the view of the real world as much as possible and thus increase the users' *Sense of Presence*. Similar to Hodges et al. [139] the user stood on a platform with railings (see Figure 2 in the work of Schuemie et al. [146]). The therapist was able to navigate the user through the virtual world by using a joystick. This gave the therapist control over what the user could see. By asking for anxiety values and measuring the heart rate, it was decided whether a user had become accustomed to a certain situation and was ready to move into more difficult areas in the VE. In the study, a within-subject design was chosen and ten subjects participated. All subjects first underwent two sessions of in-virtuo exposure and then two sessions in-vivo. The study showed that the subjects who received the VRET had achieved at least as good results. Typically, when exposed to anxiety-inducing situations, a rapid increase in anxiety is observed, followed by a slow decrease. This was also observed in both variants. For ethical reasons, the authors decided not to include a control group that received no therapy at all [145].

The same researchers conducted a follow-up study one year later [147]. They again compared in-vivo and in-virtuo therapy, this time as a between-subject design study. Now, 33 subjects participated, and the subjects were equally divided into two groups (in-vivo and in-virtuo exposure). The subjects of both groups experienced comparable scenarios. Among the scenarios were a fire escape, a rooftop passage and a mall with several floors. The results were similar to those in their first study. Both variants caused comparable reactions in the participants. The two studies [145, 147] showed comparable effects and results between in-vivo and in-virtuo exposure. In addition, a long-term effect after six months was detectable in both studies. However, they also revealed that possible further developments of the VR hardware may lead to even better results. Especially the presentation of the VE within a CAVE can lead to better results, because the VE can be presented more immersive than with the VR headset



(a) Mall (b) Fire escape (c) Roof garden

Figure 3.6: Screenshots of the virtual settings used by Emmelkamp et al. [147] and Krjin et al. [150]. (a) shows a mall with escalator, (b) a fire escape, and (c) a roof garden. Images (a), (b) and (c) from Krjin et al. [150] © 2003 Elsevier.

hardware at that time. Other studies back then showed similar positive effects of VRET [148, 149].

Jang et al. [149] placed the therapist in a different room during their study, as they had observed that they sought a lot of contact with the therapist, especially in very frightening moments. To reduce this contact, the therapist was placed in an adjacent room and could observe both the patient and the VE and communicate with the patient via microphone. Since a VR headset open at the bottom was also used here (as in the work of Emmelkamp et al. [145]), the room was darkened to increase the *Sense of Presence*, so that the environment did not influence the immersion as much.

Comparison of VR Headset and CAVE In a further follow-up study by Krijn et al. [150] to the work of Emmelkamp et al. [145, 147] (see **Figure 3.6**), for the first time a group of subjects on the waiting list was compared with subjects who received a VRET. The VRET was performed either by CAVE or VR headset. The patients who received a VRET scored significantly better in terms of perceived anxiety than patients on the waiting list. In addition, behavior and avoidance urge toward height differed between the groups. Between the VRET variants, the use of a CAVE produced a higher *Sense of Presence* in the patients, but this had no effect on the therapy results.

Juan et al. [151] achieved an opposite result when comparing VRET with CAVE or VR headset. They used a realistic looking room in which, however, unrealistic events happen. In the middle of the room, floor slabs can fall into the depths, giving the user the feeling of falling. In this study, the CAVE presentation, as in Krijn et al. [150], generated more *Sense of Presence*, but also more fear in the user. Thus, the patients were able to establish a significant correlation between presence perception and fear, which was not detectable in the study by Krijn et al. [150]. The main reason for the large difference in presence perception is mainly seen in the FoV (40 degrees diagonal). The users found the use of the CAVE more comfortable than the use of a VR headset. Furthermore, the CAVE offers the advantage that the user can still see their own body [151]. With today's VR headset technology and the possibilities of full body tracking, the results in the comparison of presence perception could be different [152].

Automated VRET Freeman et al. [153] tested the implementation of an automated VRET therapy session. A virtual coach was used, whose movements and speech were previously recorded with the help of an actor. The VR headset used was HTC Vive and the VE used was developed by OxfordVR[2]. At the beginning of the therapy, the patient is in an office scene with the virtual coach who explains a range of information about acrophobia and about the therapy (see **Figure 3.7a**). In the course of the further automated therapy session, the user ascends a ten-floor building floor by floor (see **Figure 3.7a**). On each floor, there were a number of tasks that the patient had to complete. The tasks were designed to immerse the user further into the VE. Among the tasks were, for example, playing a xylophone near one edge of the floor or throwing balls over the end of the floor. On each floor, the virtual coach asked for feedback from the user. Afterwards, the patient could decide whether he/she was ready to move to the next floor or to repeat the current floor. The subjects performed a maximum of six VRET sessions in two weeks (average 4.66 sessions) and the control group did not undergo any therapy during this time (about 50 subjects each). The results of the Heights Interpretation Questionnaire [154] showed significant improvements in the VRET group. In the control group there were hardly any differences. These effects were also stable in the four-week follow-up session. Virtual therapists or trainers are not intended to replace real therapists, but rather to support and relieve them [8].

Donker et al. [155] went one step further by developing and testing an application for the home. It is a VR Android app that can be used via smartphone. The participants used the app over a period of three weeks. There was a survey before, directly after the last session and three months after the study. In the VRET group, anxiety symptoms were significantly reduced compared to the control group without therapy. However, according to the SSQ [76], symptoms of *VR Sickness* occurred frequently. It was

[2]https://ovrhealth.com/, last accessed: May 2021

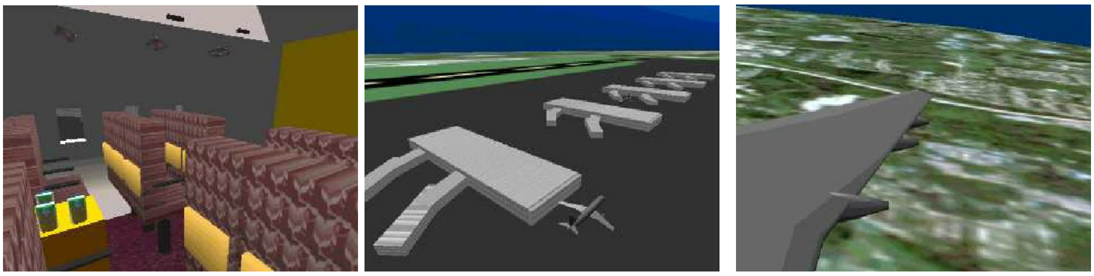
(a) Environment (b) Virtual coach

Figure 3.7: Screenshots of the VE of Freeman et al. [153]. (a) shows a part of the VE and (b) the virtual coach. Images (a) and (b) from Freeman et al. [153] © 2018 Elsevier.

observed that especially those patients who achieved a particularly high reduction of anxiety symptoms reported *VR Sickness* symptoms according to the SSQ. The authors conclude that these were primarily symptoms of *VR Sickness*, but anxiety symptoms during use, since anxiety symptoms and symptoms of *VR Sickness* partly overlap. They question the usefulness of the SSQ for *VR Sickness* surveys in anxiety therapies.

3.2.2 Fear of Flying

In the treatment of fear of flying, it is extremely complex and expensive to put patients in corresponding situations. In addition, it is even more difficult to escape from the situation in an airplane. The measure of success for a therapy is usually whether the patient is able to perform a real flight after the therapy. For this reason, therapy solutions for treatment by VRET were also investigated at an early stage. One year after the first VRET application for the treatment of acrophobia [139] the research team around Hodges developed the first application for the treatment of fear of flying with VRET using a VR headset [140]. The authors also reported that it was much more difficult and complex to design this scenario than its application for the therapy of acrophobia. The necessary environment was many times larger. Also, much more detail, animation and sound effects were needed to make the environment look as realistic as possible. The design team spent several hours measuring and photographing in a real airplane, so that they were able to create the most realistic environment possible (see **Figure 3.8**). The therapist was able to adjust various parameters during therapy. They were able to observe the VE on a screen. It was possible to determine when the airplane takes off and lands and whether turbulence occurs during the flight. The plane flew on predefined flight routes. They conducted a case study with one patient and reported that the patient was more willing to perform a VRET than a real ET. The patient underwent six VRET sessions and resulted in a significant reduction of anxiety. In addition, the patient was even able to perform a real flight afterwards. However, one month after the therapy a slight increase in anxiety was observed. This questions the long-lasting effect without therapy. Muhlberger et al. [156] showed that already one VRET session produces first positive results for anxiety reduction.



(a) Cabin of the airplane (b) Airport (c) Passenger's view

Figure 3.8: Screenshots from the VE developed by Hodges et al. [140] for the treatment of fear of flying. (a) shows the cabin view of the patient, (b) has a top view on the virtual airport, and (c) the passenger's view through the window of the virtual airplane. Images (a), (b) and (c) from Hodges et al. [140] © 1996 IEEE.

Botella et al. [157] went one step further and simulated not only the flight itself, but also the day before a planned departure at home and the boarding process at the airport. These situations are already particularly critical for patients, as they imagine the situation in the airplane more and more often and their fear increases. In the scene at home, the patient is informed via radio about the weather and flight conditions the next day. The situation in the plane included the take-off, a flight, the landing and the subsequent drive of the plane to the gate. During the waiting periods, a virtual newspaper could be read or the radio could be listened to. In addition, as usual at the beginning of each flight, there was a presentation of the pilot and safety instructions by the crew. Nine participants went through six sessions each. After the therapy, all patients were able to perform a real flight. These positive results were stable even one year after the therapy.

Rus et al. [158] compared the therapy of fear of flying using VRET and imaginal exposure. In their study, both approaches achieved very good results. However, the success of imaginal exposure depends largely on the imagination of the patient. Furthermore, imaginal exposure is more strenuous and time-consuming for the therapist, whereas

VRET sessions are relatively easy to perform after a period of familiarization.

Czerniak et al. [53] went one step further with their experimental setup. They used a CAVE environment which additionally allows the simulation of aircraft movements (see Figure 1 in the work of Czerniak et al. [53]). Feedback was also provided in the form of sound (aircraft noises and flight announcements). The therapist had similar possibilities as with the system of Hodges et al. [140]. It was possible to adjust the course of the flight (turbulence, night flight, fire and smoke development) and the landing (rough and smooth landing). In a retrospective telephone survey by Gottlieb et al. [159] 103 patients were interviewed who underwent VRET as described by Czerniak et al. [53]. The therapy had to be at least six months ago. Significant differences in the anxiety and the frequency of flights before and after therapy were found.

3.2.3 Fear of Spiders

In the early days of VRET research, studies were also undertaken early on to treat fear of spiders [141]. In 1997 the first case study was published with a patient who had been suffering from fear of spiders for 20 years, who underwent 12 VRET sessions within three months. The patient found herself in the VE in a kitchen with a virtual spider in it. The environment is called *Spider World*. With the help of a 3D mouse the patient could move around in the VE. In addition, a position tracker was attached to the right hand with the help of a bicycle glove, so that the patient could approach the spider with her hand in a virtually visible way. The spider could also be moved by the patient. In addition, the therapist could move the spider by keyboard input, move a sensor that represented the spider's position, or play pre-programmed spider behaviors. In the later course of therapy, the sensor was attached to a plush spider, so that even haptic feedback was available. Once per minute the patient was asked to give a statement of her current fear on a scale from 1 to 10. Especially the haptic feedback from the plush spider led to an enormous increase in the anxiety values. Over the three months of VRET, a significant reduction in the patient's anxiety values was observed. After the therapy, the patient was able to go out into nature more often, even in situations where encounters with spiders may occur frequently. Situations in which she encountered spiders were still considered by the patient to be scary, but the fear in these situations was manageable for her. Garcia et al. [160] used the same environment *Spider World* and tested after how many sessions (one hour each) patients are able to hold the virtual spider with haptic feedback with their hands and indicate low anxiety values. The required sessions varied between three and ten sessions. The average was four sessions. In addition, patients who underwent VRET showed better results than patients on a waiting list. Another follow-up study with the system investigated the difference in haptic feedback on patient responses [161]. It found that although there are significant differences in objective measurements (comparable to real spiders), no differences were found in subjective questionnaires.

Since the development costs for VRET scenarios can quickly become very high, a study used the computer game *Half Life* and its game editor to create a VE [162]. The VE consisted of six basement rooms, which differed in the presentation of the spiders. The size and number of spiders was varied, but also whether the spiders moved or just sat calm on one spot. In one room, interaction with the spiders was also possible. Even though the scenarios were somewhat limited by the game editor's possibilities, the cold-looking basement rooms were well suited for creating fear of spiders. The analysis of the data recorded before and after the study showed significant differences in the behavioral avoidance test, Spider Beliefs Questionnaire and perceived self-efficacy. On arachnophobia questionnaires the scores decreased and the participants were able to proceed further in behavioral avoidance tests. Michaliszyn et al. [163] made a comparison between in-vivo and in-virtuo exposure. As with Bouchard et al. [162], the video game *Max Payne* was used as the basis for this comparison. Comparable results with in-vivo and in-virtuo VRET could be achieved.

The positive effect of integrating haptic feedback could not be confirmed by Tardif et al. [164]. The remaining results were comparable to the previous studies, although only one therapy session was performed. Whether haptic feedback is particularly useful only after several sessions or whether the differences can be attributed to different applied technologies needs further investigation. Positive effects could also be demonstrated with a VRET performed by the patient themselves using a smartphone and card board [165]. For the study, a consumer app was used, which is available in app stores for smartphones. This could mean that VRET does not always have to be supervised by therapists, which would lead to a relief of the therapists. However, further studies are necessary.

3.2.4 Other Anxiety Disorders

In this section selected VRET applications are presented, which deal with other common phobias. Botella et al. [166, 167] dealt with agroaphobia. Since patients here often have problems to cope with everyday situations (where they think they are insecure), therapies are directed exactly at this aspect. They developed six scenarios that combine several everyday situations. First, the patient is in their virtual apartment, where there is a voicemail on the telephone saying that a friend unfortunately cannot come with them to the arranged shopping tour, so that the patient has to make this journey alone. As soon as the patient is ready to set off, the first task is to use the elevator to get out of the building. In this elevator there are virtual persons (the number can be adjusted by the therapist) and the therapist can, if desired, trigger an emergency in this elevator, which can become an unpleasant situation for the patient. In the further course, the patient has to complete a series of subway and bus trips to the shopping mall. Here, too, the therapist can configure how many virtual persons are in the vehicles. During the journeys, the patient must independently pay attention to which stations they need to switch from one to the other. This must be signalized by the patient. The patient should then go shopping in the mall. During the payment process, the therapist can again decide whether problems occur. **Figure 3.9** provides an impression of the scenarios. Both short-term and long-term improvements in patient well-being and behavior were reported [167].

In a study with similar scenarios, in-vivo and in-virtuo therapy was compared. Both types of therapy achieved similar results with a slight advantage in in-vivo therapy [168].

Claustrophobia is also a common anxiety disorder. Bruce et al. [169] developed a VE consisting of four connected rooms. The later rooms become smaller and narrower. The patient's task was to explore the rooms step by step, with no possibility to return to the rooms already entered. Patients explored the VE either by VR headset or on a monitor. No significant differences in presence between VR headset and monitor could be found. However, the anxiety sensation was higher when using a VR headset. One reason for the lack of difference in presence perception could be related to the used VR headset (iVisor – resolution: 800x600, ∼42 degree diagonal FoV) and the lack of head tracking.

Furthermore, social phobias are common in the population. When treating social phobias, it is especially important that the virtual avatars appear authentic. Klinger et

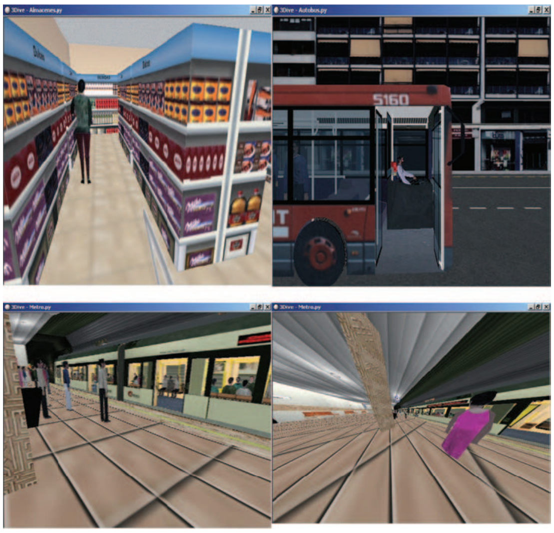


Figure 3.9: Screenshot from the VE scenarios (supermarket, bus ride and subway station) used by Botella et al. [167]. Image from Botella et al. [167] © 2007 John Wiley & Sons.

al. [170] used video recordings of real people, which they integrated in their VE as a 3D sprite and always oriented towards the user (see Figure 1 in the work of Klinger et al. [170]). The application was displayed on one monitor. No significant differences in therapy outcome between in-vivo and in-virtuo therapy could be found.

The idea of filming real people and presenting them interactively was further pursued in the therapy of social phobias. Flobak et al. [171] have recorded entire scenes of action with a 360 degree camera (see Figure 1 in the work of Flobak et al. [171]). The user views these recordings via VR headset and the actions of the scenes are designed to actively involve the user. The main aim is to address the fear of public speaking. By taking pictures of real people, the uncanny valley effect is avoided, where virtual avatars can quickly appear untrustworthy if they are not well realized. However, the interactivity of the application is lost because the recorded people cannot react to the patient's actions. In order to create a high degree of realism, a good script and good actors are necessary, while the development effort of the application itself is minimized.

Similar to Botella et al. [157], who dealt with fear of flying and simulated not only the flight itself but also the day before and the process at the airport, Luo et al. [172] developed a VE to cope with exam anxiety. In this VE the user goes through the evening before the exam, the way there and the exam situation itself (see Figures 2,3 and 5 in the work of Luo et al. [172]). In this work, virtual avatars are used. A study of effectiveness has not yet been conducted.

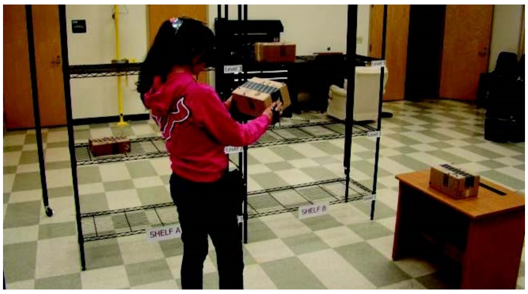
3.3 Other Therapy Areas

This section describes selected examples of other areas where VR therapy is promising. This includes the assessment and training of patients with dementia, the therapy of patients with PTSD and the use of VR for pain therapy/relief.

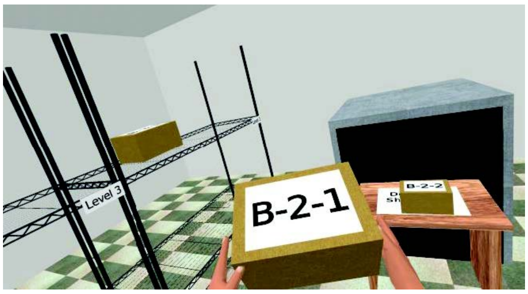
Dementia A variety of promising approaches for the assessment and training of dementia have already been developed [173]. One form of dementia makes it difficult for patients to recognize emotional changes in humans. A VR assessment tool [174] has been developed for this purpose, in which the patient is interviewed by five virtual avatars. After answering a question, the avatars react with positive or negative feedback in the form of nodding or shaking their heads. In the feasibilty study the patients showed similar behavior as in real situations and were sometimes even more communicative than in real situations.

A tool to assess Alzheimer's disease, which is a form of dementia, by VR was developed by Montenegro et al. [175]. Conventional approaches are based on paper-and-pencil tests similar to the assessment of USN. The developed tool consists of four modules:

- Memorizing up to six everyday objects in the VE and reproducing them.
- Detection of abnormalities (e.g. a flower pot hanging from the ceiling) in the VE. Such aspects are easy to realize in VR, but this requires that the rest of the environment seems plausible.
- Distinction between real and virtual sounds. This should test the mental and cognitive flexibility of the patient.
- Performing a Turing test and examining if the patient is able to distinguish a real doctor from a bot doctor. Different manifestations of the doctors (real or robot) and different ways of communication were used. They could either ask real questions or make rather confusing statements.



(a) Real Environment



(b) User's view

Figure 3.10: System developed by Bozgeyikli et al. [176] for vocational rehabilitation of people with disabilities. (a) is an image of a user using the system in the real environment and (b) shows the users' view through the VR headset. Images (a) and (b) from Bozgeyikli et al. [176] © 2014 IEEE.

Although the scenarios mentioned above could be implemented in reality, at least in some form, VE offer much more options and freedom. In the conducted study, healthy participants could be distinguished from Alzheimer patients very well.

Vocational Rehabilitation Bozgeyikli et al. developed a system for vocational rehabilitation of people with disabilities [176] and later more specifically for people with autism [177]. The goal was to evaluate and then train the current skills of the users in a cost-effective and safe environment. Three modules were developed, which contain different subtasks. Among them are the organization and order processing in a warehouse (see **Figure 3.10**), the cleaning and checking for completeness of a hotel room and the operation of a cash register in a supermarket. Some modules use a VR headset, others a CAVE.

The coach controlled the environment using a control panel on a desktop PC. Within the control panel it was possible to observe the user from different camera perspectives in the VE, distractors could be triggered, notes could be taken and results of different user sessions could be reviewed. Overall, the experience of the VE was very well received by the participants, but the *Sense of Presence* was very limited. The participants commented that the distractors had no effect on them at all, since they were aware at all times that it was only a kind of 'game'. Nevertheless, the participants in the follow-up surveys showed improvements in all trained areas.

(a) Setup (b) VE

Figure 3.11: Setup and VE called *SnowWorld* developed by Hoffman et al. [179] for pain patients with burn wounds. Images (a) and (b) from Hoffman et al. [179] © 2003 Wiley Periodicals, Inc.

Pain Reduction/Relief Another application for VR is pain reduction/relief [178]. A VE called *SnowWorld* has been developed for pain relief for patients with burn injuries [179]. Here, a VR headset without head tracking was used. The VR headset was also not attached to the patient's head, but held in front of their face with the help of a guide arm (see **Figure 3.11a**). This allowed to avoid any painful contact with wounds. The patient is automatically moved through a fictitious virtual snow world and was able to change the viewing direction using a joystick (see **Figure 3.11b**). Their task was to throw snowballs at various objects. The throwing could be triggered by a button. Hoffman et al. [179] and Faber et al. [180] showed the positive effects of this application. The patients experienced less pain during the use of the system and this effect persisted over several uses. This allowed a more comfortable treatment for the patients, as the VE distracted them from their pain. Another positive aspect of the VR headset is that the patient is 'abducted' from the real environment and does not have to observe the often painful treatment.

A graphically modernized version of *SnowWorld* was developed by Al-Ghamdi et al. [181] (see **Figure 3.12**). The HTC Vive was used with headtracking disabled. They compared the influence of the interactivity of the VE on pain sensation. Eye tracking was used to throw snowballs, as in [179] and [180]. They compared three groups of in total 48 healthy participants: an active VR group (interactivity using snowballs), a passive VR group (without interaction possibilities) and a control group without using VR. The

Figure 3.12: Graphically improved version of the *SnowWorld* by Al-Ghamdi et al. [181]. Image from Al-Ghamdi et al. [181] © 2020 Al-Ghamdi, Meyer, Atzori, Alhalabi, Seibel, Ullman and Hoffman.

participants were exposed to pain in the form of temperature stimuli. The intensity of the pain was then assessed. The participants in the active VR group rated their *Sense of Presence* and enjoyment significantly higher, while the pain assessment was significantly lower.

Similar results were obtained by Tashjian et al. [182]. They compared an interactive VR application using a VR headset and with a nature video played on a small screen. Inclusion criteria for participation in the study were a pain level of at least 3 on a scale up to 10. The origin of the pain was not considered for the inclusion. Also in this study a significantly better pain reduction could be achieved with the interactive VR application. The authors cannot say what exactly results in this pain reduction, but they suspect that it is mainly the distraction of an experience that is immersive. About a long-term effect for pain reduction no statements could be made so far, so that the use is suitable particularly during painful investigations or for rehabilitation.

Post-traumatic Stress Disorder Another area where VR therapy offers a promising alternative to the conventional ET commonly used in anxiety therapy is the therapy of PTSD [183, 184]. Patients had traumatic experiences and need support in processing them. This is similar to the therapy of anxiety, and the patient is gradually confronted with the problematic situations. PTSD can develop after a variety of different events that are not part of the normal human experience, such as car accidents, natural disasters or violence. Many applications address PTSD induced in soldiers in war [185, 186]. During war, particularly agitating and drastic situations can occur, which can accompany and impair the affected persons throughout their lifes. Here, VR offers many possibilities to relive such situations and to process them. The reliving of such situations is often not possible in the real world, or ethically unacceptable. Imaginal ET was the conventional form of therapy. The aim is that the patient learns to process the experiences and thus to suffer less from these influences. Rizzo et al. [186] developed a VR PTSD application based on a video game for therapy of Iraq war veterans. This allows the patient to relive a variety of situations that occur during war. Via remote control interface, the therapist can monitor and control the VE and trigger specific events (see Figures 1-6 in the work of Rizzo et al. [186]).

Besides traumatic experiences during war, events related to terrorist attacks are also a reason in modern time for the development of PTSD [187, 188]. Thus, the probably most severe terrorist attack in history, September 11, 2001, has affected a particularly large number of people. But especially people who were involved in the rescue operation, unfortunately often still suffer from the consequences. Difede et al. [189] developed a VR system in which the user can relive some of the events of the attack, from the collision of the planes to the collapse of the towers. Even very drastic scenes like the jump of virtual avatars out of the towers were shown. However, it is exactly such scenes that are the origin of PTSD, so they are important elements for processing the experience.

In all these systems for the therapy of PTSD, the control of the scene by the therapist is an important element. This allows a step-by-step approach at the speed appropriate for the individual patient. The VR prototypes for the treatment of PTSD are usually described in great detail, but often lack meaningful evaluations of the effectiveness of the treatments [183].

3.4 Discussion

After the effectiveness of VR therapy has been demonstrated in recent years [7, 136, 137, 138, 190], the exact mechanisms of VR responsible for the positive results are still not well understood [7, 190]. Also, the exact benefits of VR over desktop-based systems should be investigated. Due to the further development and cost reduction of VR technology in recent years, the use and acceptance of VR in the clinical environment is increasing [7]. Especially mobile VR variants offer a great potential, because the costs and the necessary effort for using VR are very low. This allows, e.g., a training at the patient's home, which can relieve the medical staff [155]. Virtual coaches can also be used to support the medical staff [153]. Often it is difficult to analyze the developed VE more precisely in this area. Especially in the publications with a main part from the psychological domain, the focus is often on the studies, but the developed prototypes are not described in detail. A more detailed description of the VR content used could be very helpful in helping to answer the question which VR aspects have a particularly large effect.

As announced at the beginning of the chapter, the aspects of the SWOT analysis of Rizzo and Kim [17] from 2005 will be discussed. The recognized strengths and opportunities of VR are still valid and are subject of current research, e.g. telerehabilitation. Especially the higher ecological validity is still one of the major benefits. The mentioned weaknesses have become less severe in recent years. For example, modern displays have significantly improved the quality compared to the past, there are wireless VR solutions, and interaction possibilities have also become much better with modern tracking systems and input devices. Due to higher computing power and the use of machine learning, data analysis can also be performed much faster and with more meaningful results. Problems with side-effects of VR systems still exist today, but could already be reduced. The mentioned threats, such as missing cost and therapy advantages, are also only partially given. The development of VR applications has become easier and cheaper due to modern game engines. Therapeutic advantages have been shown in the last years, even if the exact mechanisms are still not completely understood. Interdisciplinary teams, which are responsible for the development of such rehabilitation systems, can develop systems, work according to ethically justifiable regulations and clarify the expectations on the systems. The potential of VR in therapy and rehabilitation has thus become even greater in recent years. Already in 2005 the strengths and opportunities outweighed the weaknesses and threats. Most of the weaknesses and threats have been eliminated with the help of the latest technology, and the acceptance of technology is growing steadily.

It was observed that much more work already exists in the field of VRET than for cognitive rehabilitation. In the following, specific aspects of cognitive rehabilitation and VRET are discussed.

Cognitive Rehabilitation While the treatment of anxiety therapies usually focuses on mapping the situations that cause anxiety, cognitive rehabilitation systems can be roughly divided into two categories:

- Systems for the representation of realistic everyday tasks
- Abstract systems that realize paper-and-pencil like tasks

Systems cannot always be assigned to exactly one category, but lie in a spectrum in between. An example of a very realistic system for an everyday task is the supermarket shopping system by Mondelini et al. [117, 118] (see **Figure 3.2**). A very abstract system is shown by Knobel et al. [133], who transferred a cancelation task, which is normally executed with paper and pencil, to a VR system (see **Figure 3.5**). In the spectrum in between are the works of Belger et al. [115] and Yasuda et al. [130] (see **Figure 3.4**). Both move in a realistic environment with realistic elements, but use relatively abstract tasks. Both categories can be successful. Future studies must, however, show more precisely whether systems that depict a larger proportion of everyday tasks offer a better transfer of everyday life. A major criticism of most studies is that long-term effects of VR-based rehabilitation are not investigated. Most studies report positive effects shortly after training, but make no statement about a long-term positive effect [107].

It is also essential to pay attention to patient safety. Particularly in the case of patients with disabilities, such as paralysis, care must always be taken to ensure that, despite visual isolation from their real environment, patients do not lose their orientation or balance and may be injured. It would therefore be an advantage if applications could also be used while sitting. This can increase the potential group of users.

Furthermore, the acceptance and willingness of hospitalized patients to use VR was investigated [191]. After excluding patients by a variety of criteria, only about 33 % of the remaining patients were willing to try VR technology. This represents an extremely small fraction of the possible subjects in the study (5.9 %). These patients tended to be younger people, who are often more open to new technologies. The subjects who tried VR reported mostly positive and pleasant experiences. Especially in the dreary and possibly boring clinical routine, VR offers a great entertainment potential. Some patients described VR as a kind of escape from the clinical environment. At the same, time deficits of the patients can be trained in a pleasant form. Future work should therefore also deal with the topic of how elderly people can be convinced of the potential of VR.

Elderly people are often skeptical about new and unfamiliar technology, but most are more interested and understand it better after the first use. The cable of VR headsets is perceived as disturbing and creates insecurity for the user. Elderly people also tend to forget the button assignment. However, this is often only a matter of practice, but the controls should still be kept as simple as possible. The target group that is mainly addressed by VR headset manufacturers is young and technically minded. Future work should explore ways to make VR headsets more accessible to elderly people. For example, the texturing of the controller buttons could be more distinctive, so that a better distinction is possible [192]. Young people, on the other hand, are often used to modern technology and video games, which also increases the demands on VR systems. They have to look appealing and the usage has to feel modern, so that young people can also enjoy them [117].

Virtual Reality Exposure Therapy For most anxiety disorders, the therapy consists of placing the patient in the appropriate anxiety-causing situation so that the patient can learn to deal with these situations and possibly understand that the anxiety is often unfounded. For many anxiety disorders (fear of flying or fear of heights), for example, it is time-consuming to first put the patient in the appropriate situations.

Previous studies have already shown how great the potential of VRET is [16, 52], especially in the treatment of anxiety and pain management [193]. Studies on VRET of depression and stress are still very underrepresented [193]. However, often only small sample sizes are used and control groups are often completely missing [135, 137, 194]. In addition, most studies do not consider the effects of therapies on the quality of daily life [16]. Often not only the situation itself is frightening, but also the thoughts and preparation before. This can lead to such great fears that patients no longer want to face the situation. Some studies have addressed this by realizing preparatory situations [157, 172].

Special challenges arise in the treatment of social phobias, because the interaction with these avatars must create a feeling of real social interaction. Thus, there is a fine line between the choice of abstract representation or a most realistic representation of the avatars [195]. Here, the uncanny valley effect can occur [119, 196], where some avatar properties become very realistic, but other aspects look artificial.

The lower initial threshold for the therapy could have a positive influence especially in the case of social phobia, since it is not necessary to train with real persons and thus a possible existing shame threshold is avoided [166, 197]. In general, the VRET technique can have a motivating effect on patients, since the therapy experience can be improved by possible gamification elements.

Therapists need training to learn the VRET technique, so that they can competently explain the necessary interactions to patients. This may deter therapists who are not so technically experienced. However, the VRET procedure can be less demanding for the therapist than, for example, an imaginal ET session [158]. Furthermore, it can save him/her time, which can lead to cost savings [198].

Comparisons between CAVE and VR headset in the use of VRET are already several years old [150, 151]. Due to the further development of both techniques, new direct comparisons would be desirable. Especially the progress in today's VR headsets was tremendous in the last years. Possible 'tricks' to darken the environment [145, 149], because the headset is open to the outside, are no longer necessary because today's VR headsets are completely closed. These technical enhancements may also reduce any potential advantages of in-vivo therapy [168] over VRET [52]. In their comparison of CAVE and VR headset Juan et al. [151] had mainly emphasized the advantage of the CAVE that the patient is able to see their own body, which can increase the *Sense of Presence*. With today's tracking technology, it is also possible to create this effect for VR headsets [152]. A big advantage of modern VR headsets compared to CAVEs are the much lower costs and the much smaller space requirement. For therapists in private practice, CAVE solutions would be almost impossible to realize.

With VRET systems for the treatment of anxiety, one problem is to detect *VR Sickness* symptoms. Symptoms of *VR Sickness* which are recorded with the SSQ [76] often overlap with typical symptoms of anxiety. In the study by Donker et al. [155], patients who had the supposedly greatest problems with *VR Sickness* (according to the SSQ), however, made the greatest progress in therapy. The authors concluded that they did not experience increased *VR Sickness*, but that their anxiety symptoms were particularly severe, so that they were able to cope with their anxiety particularly well during VRET. New methods for detecting *VR Sickness* would be desirable for evaluating VRET systems.

4 iVRoad: Virtual Reality Road Crossing for Unilateral Spatial Neglect Rehabilitation

As part of the thesis, a VR application called iVRoad was developed. It is a VE, where the user can perform virtual road crossings in a safe environment. It aims to diagnose, and in the future, treat patients with USN. For this purpose, first the decision process to choose this direction is described. Based on that, the application was developed in two major iterations. The first iteration was developed to assess *Difficulty Factors* of virtual road crossings (**RQ1**) and get familiar with the development of such an application. The application was evaluated by 60 healthy participants, and factors that could be used to adjust the task difficulty were identified [199]. In the second iteration, the focus of the development was on the applicability to stroke patients (**RQ3**) and the investigation of factors that could be suitable for an assessment of USN patients in order to be able to distinguish them from stroke patients without USN and thus diagnose neglect (**RQ2**) [200, 201]. This application was evaluated with 18 stroke patients. The two applications are described and the results of the two performed studies are presented. The chapter ends with a summary and an outlook for possible research directions based on this work and presents the potentials of a training application based on the developed applications.

4.1 Decision Process

The first step was to find a scenario which fits into the rehabilitation process of stroke patients and which could benefit from the usage of an immersive VR system. After research in the literature and discussions with different neuropsychologists and other experts it was clear that the training of ADLs is a promising way. Especially road crossing was mentioned next to other everyday tasks like shopping in the supermarket or preparing meals [89]. During discussions with the cooperation partner of the University Hospital Leipzig it was mentioned that there is a kitchen for patients in the clinic, where therapists prepare meals together with the patients to relearn the respective processes. Since this was an already used tool in the clinic, it was decided against this orientation for a development of a VR application. Much more interesting are everyday tasks that cannot be trivially performed in the clinic or are possibly even too dangerous to perform/train in real life. These aspects apply at least in part to both the *supermarket shopping scenario* and the *road crossing scenario*. One of the cooperation partners was already working on a project in the field of VR and supermarket shopping. Therefore, the decision was made to develop a road crossing application as a promising alternative. Especially patients with USN have problems performing save road crossing, which can lead to dangerous situations.

4.2 Related Work on Road Crossing

In order to develop a system for stroke patients to cross roads in a VE, it is essential to consider traffic-psychological aspects and previous research. In the literature, the traffic behavior of children and elderly people is often studied. Novel training possibilities are also explored, in particular for these two groups as they are especially at risk in road traffic.

Research on Road Crossing Behavior McComas et al. [202] have shown that children can be taught the order of steps to be taken after only a short time using a screen-based virtual road crossing system. A study by Thomson et al. [203] showed significant improvements in the ability to cross roads after four training sessions. Comparable results were also obtained by Morrongiello et al. [204]. Here, children who used a VR training program with a VR headset made between 75 and 95 % fewer errors after testing than children from the control group who played a video game independent of road crossing with the same input devices. The difference in training with children is that they need to learn the ability to cross roads safely.

Patients, on the other hand, must learn to deal with their impairments and successfully apply compensation techniques in order to cross roads safely again. In most cases, they do not have to re-learn the procedures for safe road crossings, but learn to cope with the variety of stimuli. Most stroke patients are already at an advanced age and therefore there are further problems with their handling in road traffic. Elderly people, who slow down due to the normal aging process, also have problems [205]. Thus, various publications on traffic psychology deal with the safe crossing of roads. According to Simpson et al. [206], a road crossing is considered safe if there is at least 1.5 seconds between leaving the road lane and the arrival of the vehicle at this point. Road crossings are very diverse and based on a lot of different difficulties and influencing factors, e.g. the traffic speed and the number of lanes. People under time pressure tend to pay more attention to the distance of the car than to the speed, which can lead to dangerous situations [207, 208, 209]. This effect seems to be even more pronounced in older people. The problem of correctly assessing the speed of vehicles was identified in further studies and thus seems to represent the greatest risk [210]. Especially older people pay less attention to the second lane [211]. Because of physical limitations, older people often lack the ability to adjust their walking speed when critical situations arise [212]. Bahari et al. [213] also reported that people tend to assume smaller distances between cars when the approaching vehicle is smaller (e.g. a motorcycle). These factors influence the subjective difficulty of safely crossing a road.

This is consistent with observations of virtual road crossing in previous studies [207, 208, 209]. Similarly, the participants paid more attention to vehicle distance than to vehicle speed. In addition, people often have problems to correctly estimate the speed of vehicles when two or more vehicles are approaching. This often leads to an underestimation of speed, which again increases the potential danger [214]. Distraction is another factor that often leads to accidents [215]. Especially for older people, even having a conversation can be so distracting that they may neglect road traffic [216].

Maruhn and Hurst [217] investigated the effects of the representation of a virtual avatar on road crossing tasks in VR. They compared three conditions: no virtual avatar representation, virtual hands with and without finger tracking. They could not find any differences in the *Sense of Presence* between these conditions. Virtual body ownership was stronger for the conditions with finger tracking in comparison to no finger tracking. They also found that in the two conditions with a virtual avatar, participants chose significantly smaller gaps to cross the road. For all three conditions the number of collisions was equal.

Figure 4.1: Real (left) and virtual (right) location of the study performed by Feldstein et al. [219] to compare real and virtual road crossings. Image from Feldstein et al. [219] © 2019 Elsevier.

Bhagavathula et al. [218] showed that for most of the tasks there is almost no difference between virtual and real road crossing. However, significant differences were observed in the estimation of speed and distances, which are crucial aspects to assess road crossing decisions. Feldstein et al. [219], however, identified differences between real and virtual crossings (see **Figure 4.1**). In real crossings, participants in their study tended to consider temporal distance (e.g. time-to-contact), whereas in the VE spatial distance had the greatest influence. Vehicle speed was neglected, which led to dangerous situations and errors. Therefore, further studies are needed with very similar scenarios in order to obtain clear results.

Pala et al. [220] compared virtual road crossings performed in a CAVE and with a VR headset (HTC Vive Pro). In earlier papers, this working group mainly investigated virtual road crossings by using a CAVE [211, 212]. They were able to show that the results with a VR headset are very similar to the results with a CAVE. The differences between younger and older participants were clearly visible with both modalities. This shows that VR headsets are suitable for performing virtual road crossings despite some limitations like smaller FoV.

Road Crossing for Assessment and Training The potential of the road crossing scenario for assessment and training of USN patients was recognized early on. Weiss et al. [221] and Katz et al. [222] tested a screen-based virtual road crossing system on USN patients. The patients' task was to bring a virtual avatar (from third-person perspective) safely across a road with a crosswalk (see **Figure 4.2**). The direction of view could

Figure 4.2: Image of the desktop-based VE used by Katz et al. [222] to train virtual road crossing to stroke patients with USN. Image from Katz et al. [222] © 2005 Taylor & Francis.

be changed using the arrow keys, and a mouse click could be used to start the road crossing. The system had seven levels of difficulty. For example, the vehicle speed and the number of vehicles were changed in the higher levels. Patients with USN needed more time for their decisions and were able to complete fewer levels than the healthy participants in the control group. The achieved results showed a similar improvement as with conventional visual search tasks. During real road crossings, the number of looks to the left increased in the comparison of before and after training.

Another road crossing system was developed by Kim et al. [128, 129], which was used for both the assessment and training of USN patients using a VR headset. The general idea of this system is that a virtual avatar is standing in the middle of a road on a pedestrian crossing and the user's task is to detect approaching vehicles before they collide with the avatar. By pressing the mouse button, the user indicates that they recognized a vehicle. Visual and auditory cues were used to improve the detection. They used the error rate, *Decision Time* and deviation of the viewing behavior from the actual center to evaluate the performance of the users. Significant differences were found between patients with USN and healthy control subjects, especially in the response to stimuli

(a) VE and setup by Navarro et al. [223]

(b) VE by Wu et al. [224]

Figure 4.3: (a) shows the setup and a part of the VE of the low-cost system that was used by Navarro et al. [223]. (b) shows the VE and the simulated scotoma in the middle of the screen created by Wu et al. [224] to assess the influence of the impairment on virtual road crossing. Image (a) from Navarro et al. [223] © 2013 Taylor & Francis and (b) from Wu et al. [224] © 2018 Wu, Ashmead, Adams and Bodenheimer.

from the contralateral side.

A more realistic road crossing task was developed by Navarro et al. [223]. They also used a desktop-based application, combined with a head tracker for head movements and a joystick for navigation in the VE. The task was to cross two roads next to a roundabout (see **Figure 4.3a**). They also found significant differences in the performance between patients with and without USN and healthy controls. The number of unsafe crossings was almost equal between the groups, which indicates that the potential for risky behavior is not influenced by stroke. Wu et al. [224] evaluated the impact of a simulated macular degeneration, which affects the perception, on virtual road crossing performance. This simulated impairment resulted in a longer waiting period before crossing the road, and as the scotoma increased (see **Figure 4.3b**), the gaps considered safe to cross also increased in size.

4.3 Road Crossing Difficulty Factors for Cognitive Rehabilitation

There are several requirements that facilitate an effective rehabilitation. In rehabilitation it is very important to expose patients to suitable tasks and their difficulty. If the tasks are too simple, the patient can quickly become bored and lose the desire to train. Too difficult tasks, on the other hand, can cause the patient to become frustrated and lose the desire for further training. It is the *continuous training* that leads to successful rehabilitation. Therefore, motivating and suitable tasks should always be emphasized. Motivation can also be supported by the integration of motivational elements such as those familiar from video games. Another factor is the reduction of pain [225]. It is advantageous if the patient is distracted from pain by the task. This can lead to longer and more pleasant assessment/training sessions and can be achieved especially through immersive experiences [182]. Therefore, already known road traffic factors from the literature should be evaluated for their influence on the task difficulty in order to be able to perform better adjustments to the tasks later on. In the following section, the developed prototype to evaluate *Difficulty Factors* in virtual road crossing tasks is presented (**RQ2**). With the help of the VE a user study with 60 participants was performed. This user study and its results are described in detail. At the end of this section, the conclusions drawn from the results are discussed, and how these results can be used for virtual road crossing tasks in rehabilitation. Parts of the texts and the results of the following section were already published in:

- **Sebastian Wagner**, F. Joeres, M. Gabele, C. Hansen, B. Preim, and P. Saalfeld, "Difficulty Factors for VR Cognitive Rehabilitation Training–Crossing a Virtual Road," *Computers & Graphics*, vol. 83, pp. 11–22, 2019. [199]

Figure 4.4: Panoramic image of the first developed virtual road environment to assess *Difficulty Factors*. Image from Wagner et al. [199] © 2019 Elsevier.

4.3.1 System

In order to be able to investigate *Difficulty Factors*, a virtual road scene was developed. It consists of a two-lane road with a length of 600 meters. The user is located at the roadside in the middle of this road (see **Figure 4.4**). This environment was developed with the game engine *Unity* (version 2017.2.0f3) and is based on a fictitious urban residential area. For the construction of the virtual world, assets from the *Unity Asset Store* were used. Both the development and the study were carried out on a Windows 7 desktop PC. This computer was equipped with an Intel Xenon X3480 processor with 3.07 GHz, an Nvidia Geforce GTX 1060 with 6 GB and 16 GB RAM. The VR headset HTC Vive is used as output device (recall Section 2.2.1). In addition to a visually detailed and suitable VE, sound is used to create an even more realistic environment. The VE gives the user sound in the form of a constant city-like background noise level and engine sounds for every car. These vehicle sounds improve the detection of approaching vehicles, especially for users with visual deficits.

Different traffic situations were simulated (see Section 4.3.2) and the task of the users was to decide whether or not the occurring gap in the road traffic allowed a safe road crossing. By pressing the trigger on the HTC Vive Controller, the user signals that they

Figure 4.5: Avatar crossing the road between two cars. Image from Wagner et al. [199] © 2019 Elsevier.

would now cross the road and a virtual avatar starts to walk. The avatar then tries to successfully cross the road at a speed of 1.45 m/s while the user stays at the roadside (see **Figure 4.5**). This speed is based on Morgenroths [226] observation of the walking speed of 6000 Germans. In the VE, the avatar cannot be stopped or accelerated.

It was decided to let an avatar cross the road instead of the user due to the following reasons:

- A feeling of fear can arise if a virtual car is approaching in highly immersive environments. This fear may lead to sudden movements that could cause injuries and should therefore be avoided. This should also prevent the occurrence of motion sickness.
- Feldstein et al. [227] report about an unease among users when a car approaches them directly in the virtual world. Furthermore, the target group of the system are patients with cognitive and possibly additional motor impairments so that the operation should be as simple as possible. No physical exercise is necessary so that physically impaired patients can also use the system.

The avatar has to travel a distance of 6.75 m until it comes to a stop on the other side of the road. Each vehicle lane is 3 m wide. In addition, there are 0.75 m on the respective sidewalks. The structure of the road scene is shown in **Figure 4.6**. This road width is oriented to a typical German road.

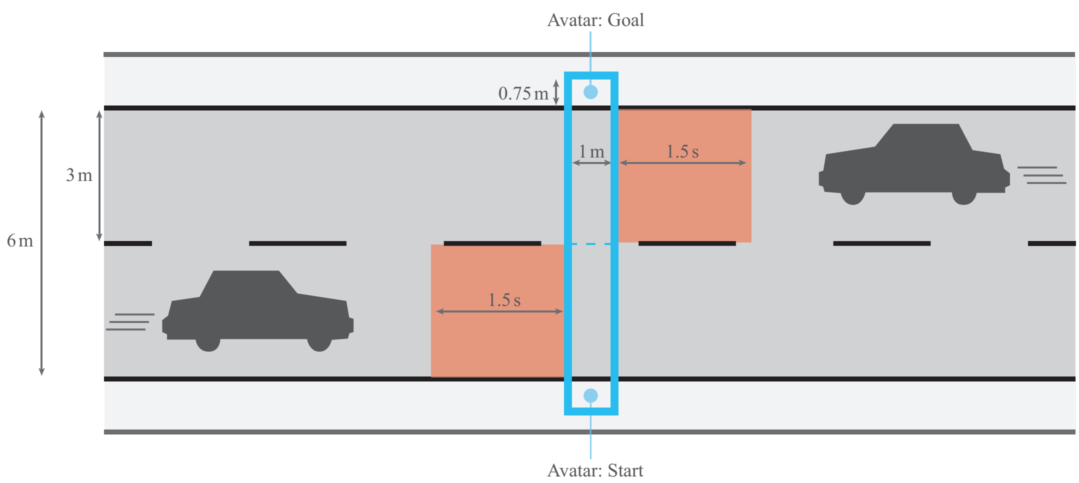


Figure 4.6: Schematic structure of the road scene. Image from Wagner et al. [199] © 2019 Elsevier.

It depicts the start and end point of the user and the implemented 1 m wide corridor in which the user crosses the road. In addition, the 1.5 s safety time distance (recall Section 4.2) to approaching vehicles is shown, which must be maintained so that a crossing is considered safe. This was realized with the help of bounding boxes for collision detection. As soon as a vehicle moves into one of the corresponding areas, the corresponding events (e.g. violation of the safety distance) are triggered and recorded in a log file. In addition, the events of the start and arrival of the avatar's target are stored with an appropriate timestamp.

The task was performed by the user while standing. Precise head tracking thus ensured that the user's viewing height in the VE corresponded exactly to the same height as they perceive in the real world. This way, the user is placed in familiar size/visibility ratios in relation to the vehicles and the environment, and this supports the immersion. All vehicles used had almost the same shape and mainly differed in their colors. Vehicles of different sizes would be another *Difficulty Factor*, as they either obstruct visibility or actively influence users' decisions [213]. No pedestrians were integrated into the VE, as they have a potential for distraction and could be a *Difficulty Factor* on their own.

4.3.2 Study

This VE provided the basis for the conducted study. For this purpose, with the help of related work from this field (recall Section 4.2), suitable traffic factors that may have an influence on task difficulty were highlighted. In addition, in order to evaluate their influence, different measures were selected to assess behavior and performance. The selected factors (independent variables) and quantitative measurements (dependent variables) are presented in detail in the following. Subsequently, the participants of the study are introduced, and the task and the entire procedure of the study are presented.

Independent Variables The traffic factor that can have an influence on the task difficulty are the independent variables. The following four traffic factors were chosen: *Relevant Lanes*, *Traffic Speed*, *Gap Sizes*, and *Number of Vehicles*. These factors consist of different levels and are introduced in the following.

Relevant Lanes is defined as a factor with three levels. Since the developed environment is a two-lane road, right-hand traffic results in three variants. Vehicles can approach on the lane close to the user from the left (hereafter, *Close Lane* condition) or on the far lane from the right (hereafter, *Far Lane* condition). The third variant is traffic from both directions (right-hand traffic). This condition is called *Both Lanes* condition in the following. Here, gaps opened in both lanes at the same time. Traffic in countries with left-hand traffic is not considered in this study.

Traffic Speed was defined with two levels: *30 km/h* and *50 km/h*, as these are often used in literature [210, 211] and occur in German inner city traffic and residential areas.

Gap Sizes were determined by dependence on multiple parameters. For this, it was assumed that the pedestrians had to walk 0.75 m past a given lane to be considered safely out of that lane. Under consideration of this safety distance, lane width, walking speed, and vehicle speeds, gap sizes were selected such that roughly 50 % of all scenarios enabled safe crossing, 40 % only enabled unsafe crossing, and 10 % would end in collision if participants started walking after the gap opened. *Gap Sizes* were set to *50 m*, *65 m*, and *80 m*.

Two levels were also defined for the *Number of Vehicles* in the virtual scene: one condition under which a total of eight vehicles were in the traffic scenario (hereafter, *Low Vehicle* count condition) and one condition with 24 vehicles (hereafter, *High Vehicle* count condition). This factor defines the overall *Number of Vehicles* in the scene, i.e. the *Number of Vehicles* per lane deviated between the *Both Lanes* condition and the *Single Lane* condition. This approach was chosen because the *Number of Vehicles* was varied to manipulate the overall visual information in the traffic scene. This fact is

Table 4.1: *Difficulty Factors* and their levels. Table from Wagner et al. [199] © 2019 Elsevier.

Difficulty Factor	*Factor Level*
Relevant Lanes	*Close Lane*
	Far Lane
	Both Lanes
Traffic Speed	*30 km/h*
	50 km/h
Gap Sizes	*50 m*
	65 m
	80 m
Number of Vehicles	*Low Vehicle*
	High Vehicle

particularly interesting for patients with visual impairments, as many vehicles may require more cognitive capacity.

Overall, the combinations of these factors resulted in 36 traffic scenarios. **Table 4.1** gives an overview of the four *Difficulty Factors* and their respective levels.

Dependent Variables Three dependent variables were selected, comprising a variation of behavioral and participant-subjective variables as indicators for trial difficulty. *Errors* were recorded for each trial. To this end, participants' results were classified into three categories:

- *Correct*: participants crossed the road safely or did not cross the road in a scenario that did not allow for safe crossing.
- *Missed opportunity*: Participants did not cross the road in a scenario which allowed for safe crossing.
- *Unsafe crossing*: Participants crossed the road in a scenario in which safe crossing was not possible or they simply crossed the road too late. It was not distinguished between violations of the 1.5 s safety margin and collision events.

The amount of *Head Turns* was counted in each trial. This number represents the number of visual attention allocations to different road directions in order to make a decision. It was believed that the number of required visual attention allocations is an indicator for how difficult the decision is to make. Navarro et al. [223] found differences between healthy people and patients with USN. A head turn was registered whenever the participants turned their heads to either side by more than 30 degrees off the center position. Head turns were counted from the beginning of each trial until the decision was made, i.e.:

- if a participant pressed the button to cross the road, the button press event concluded the counting period,
- if a participant did not press the button in a trial in which safe crossing was not possible, the event of the gap opening concluded the counting period,
- if a participant did not press the button in a trial in which safe crossing was possible, the time at which safe crossing was mathematically no longer possible concluded the counting period.

The number of head turns was normalized against the head turn count duration. The resulting *Standardized Head Turn Count (SHT)* (see Section 4.3.3) was used in statistical analysis.

Participants were asked to provide their *Subjective Estimation* of the difficulty to decide if they should cross or not in each scenario. They were asked to rate this estimate on a 6-point Likert scale with the verbal anchors: “Very Easy”, “Easy”, “Slightly Easy”, “Slightly Difficult”, “Difficult”, “Very Difficult”.

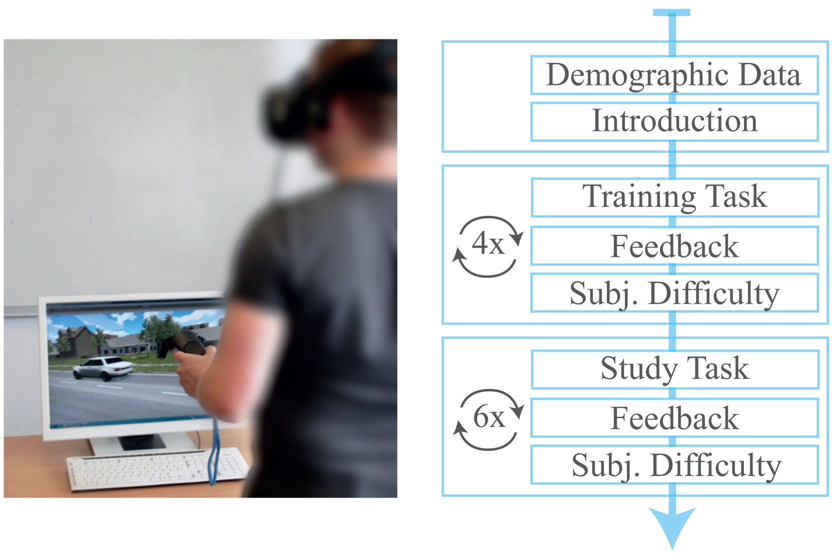
Participants The participants of the study were guests of the annual Long Night of Science at the University of Magdeburg in 2018. 60 participants (24 female, 36 male), aged between 16 and 79 years (Q1 = 21 years, median = 49 years, Q3 = 66 years), took part in the study. Eight participants were attending secondary school at that time, 19 participants were attending university, 32 were working and one participant was retired. Out of the 60 participants, 40 stated that they had no experience with VR devices, 19 participants stated that they had some experience and one participant did not answer the question.

An age of at least 16 years was required for participation, as it is possible to obtain a driver’s license in Germany from this age, and a corresponding feeling for road traffic should be present. Another aspect is the height of the participants. Since the camera height in the VE corresponds to one’s own height, almost full-grown people are required. This ensures a sufficient overview of the traffic situation.

Tasks The user were standing at the side of the two-lane road and their task was to decide whether they consider it safe to cross the road by pressing the trigger of the controller. Several vehicles approached the user. There were smaller gaps between the vehicles, but these were not sufficient for crossing under any circumstances. However, there was one traffic gap per trial, which corresponded to the already presented factor of *Gap Size*. After the user pressed the trigger of the controller, as described in Section 4.3.1, the virtual avatar started moving to cross the roads. The user also had the possibility not to start any crossing. This was meant to ignore the gap if the user considers it impossible/not safe. Since there were trials with impossible gaps, due to the combination of *Gap Size* and *Vehicle Speed*, this was necessary in some trials.

Experimental Procedure Participants were introduced to the broader purpose of the study, the devices, the VE, and their tasks. Overall, participants then underwent ten trials: four training trials and six test trials out of the 36 scenarios in which data was collected. The training trials should enable the user to familiarize themselves with the system and the interaction. The first two training trials encompassed a scenario with two cars driving in opposite directions and participants crossing once the cars had passed. The remaining two training trial scenarios consisted of two cars following each other and, thus, opening a gap. Scenarios were assigned to participants such that each participant's trials were balanced on each of the factors (e.g. each participant saw three scenarios each in the *Low Vehicle* number condition and in the *High Vehicle* count condition, etc.). The order of trials was randomized for each participant.

After each trial, either at the end of the trial's traffic the avatar reached the other side of the road or the avatar would collide with a vehicle, the screen faded to black and a feedback text was displayed for 3 s. This also prevents the user from seeing a possible collision between the avatar and the vehicle, as this is hidden. Generally, the feedback only read "Task complete". However, if an *Unsafe Crossing* event was



(a) Participant using the prototype (b) Procedure of the study

Figure 4.7: Overview of the study setup and procedure. Images (a) and (b) from Wagner et al. [199] © 2019 Elsevier.

detected, the feedback read “Too close, unfortunately” instead. After each trial was completed, the experimenter asked the participants to verbally provide their subjective difficulty estimation. The experimenter started the next trial when the participants indicated that they were ready to continue. The overall experiment lasted about 15 minutes per participant. **Figure 4.7** gives and overview on the study setup and the whole procedure.

4.3.3 Results

This section first describes the steps taken to standardize the head turns, describes excluded data and outliers, and then presents the results of the study.

Standardized Test Variable Head Turns The participants’ head turns were recorded in the period between the start of the trial and the moment when a decision was made by the user. Therefore, head rotation serves as an objective measure of the visual effort required to assess a traffic situation. However, since the trial duration differs greatly due to the different traffic conditions, the potential for possible head turns was also different. In particular the six trials with single-lane traffic, low speed, and high number of vehicles had a considerably longer head turn counting duration than all other trials. Thus, there may be large differences in the number of head rotations, as the task was longer in these trials (see **Figure 4.8**). To address these differences, a standardized test variable was developed. To achieve this, a linear regression model was generated which predicts the number of head turns for a given head turn counting duration:

$$PHT = 2.81 + 0.12s^{-1} * t_{HTC}$$

where PHT (Predicted Head Turns) is the predicted number of head turns by the model and t_{HTC} is the duration of the head turn counting period (see **Figure 4.8**). The standardized test variable SHT (Standardized Head Turns) was then generated by calculating each data point’s residuals from the linear model:

$$SHT_i = AHT_i - PHT_i$$

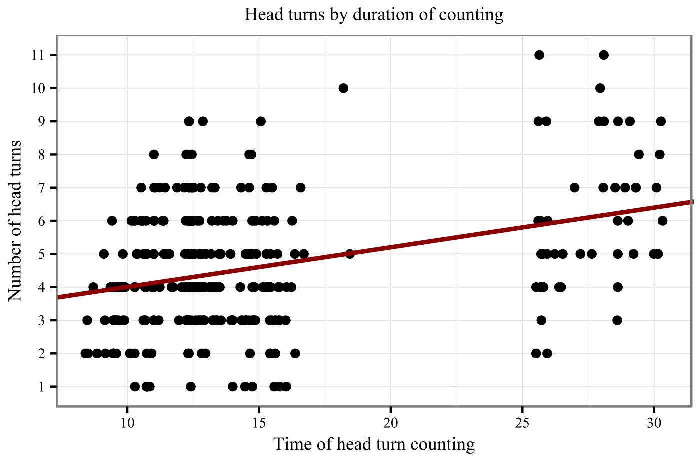


Figure 4.8: The data points represent all trials performed during the study. This shows the length of time the *Head Turns* were recorded and the number of *Head Turns*. The two data point groups are created by the different length of the trials. The group in the right diagram area represents the single-lane trials with a *High Number of Vehicles* and a *Traffic Speed* of *30 km/h*. Image from Wagner et al. [199] © 2019 Elsevier.

where i is the trial index and AHT (Absolute Head Turns) the absolute number of head turns counted in each trial.

Note: The linear model reported here was generated after eliminating statistical outliers (see next section).

Data Exclusion and Outliers The overall data set consisted of data from 360 trials (six trials each for 60 participants). However, prior to further data analysis, some of the recorded data sets were excluded from the analysis for some or all dependent variables.

In total 16 trials (4.4 % of 360 trials) were excluded because the button was pressed too early by the participants. This resulted in a subsequent collision with vehicles or the avatar successfully crossed the road before the first vehicles of the trials arrived at their position. This behavior could have been restricted by the application beforehand.

To identify outliers based on the dependent variables, the mean SHT was calculated for all participants. The distribution of those personal means across the sample was then generated and all participants exceeding a window of +/- $2\,\sigma$ (standard deviations) were excluded from further head turn analysis. They were still included in the analyses for the remaining dependent variables. Three participants were excluded as outliers (17 trials; 4.7 % of 360 trials – one trial of one of the three participants had been eliminated in the previous step).

The same method was applied for subjective difficulty rating, but no statistical outliers were identified. However, all trials in which participants received the "too close" feedback were excluded, as the feedback was shown prior to the assessment of the subjective rating of each trial and may have biased participants' perception of the trial. In this step, data from 92 trials were excluded (25.6 % of the initial 360 trials). It should be noted that all of these trials included all trials with the traffic scenario *80 m Gap Size*, traffic in *Both Lanes*, *50 km/h Traffic Speed*, and a *High Number of Vehicles*.

Errors Chi-squared (χ^2) tests were conducted to investigate each factor's impact on the errors committed by the participants. All correct events (i.e. *Safe Crossings* and *Correct Waiting* events) were summarized to the category of *Correct* events, since both event types were the correct reaction in these situations. *Unsafe Crossing* events and *Collision* were also summarized in one category for the statistical analysis.

The total number of *Missed Opportunity* events was so low that they had to be excluded in the analysis of the *Gap Size* and *Relevant Lanes* factors to ensure reliable χ^2 tests. Significant results of the χ^2 tests are listed in **Table 4.2**.

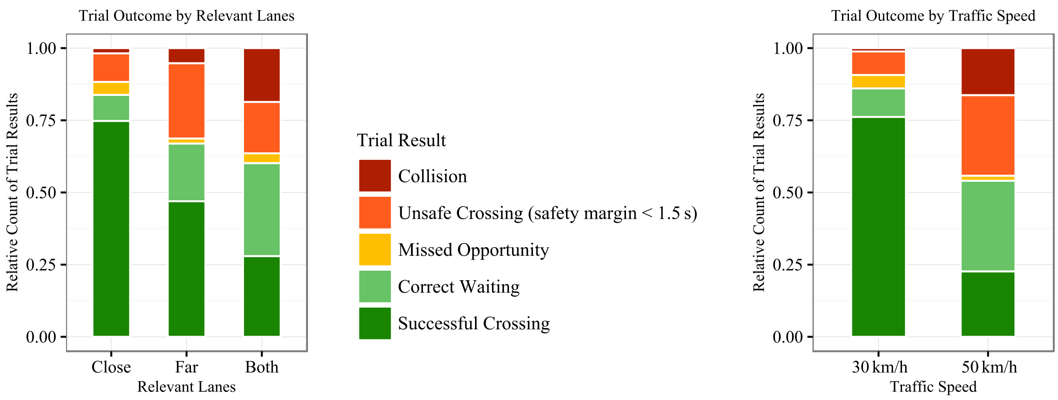


Figure 4.9: Error results for *Relevant Lanes* and *Traffic Speed*. Image from Wagner et al. [199] © 2019 Elsevier.

Table 4.2: Summary of the statistical results of the X^2-tests for *Errors* and of the ANOVAs for the standardized *Head Turns* and *Subjective Difficulty*. Table from Wagner et al. [200] © 2019 Elsevier.

Effect type	Factor	df	χ^2	F	p	sig	η^2	Effect
Errors								
Main effects	*Relevant Lanes*	2	19.33		<0.001	*		
	Traffic Speed	2	53.96		<0.001	*		
Head Turns								
Main effects	*Relevant Lanes*	2		27.13	<0.001	*	0.135	medium
	Traffic Speed	2		8.56	<0.010	*	0.021	small
	Gap Sizes	1		3.16	0.040	*	0.016	small
	Number of Vehicles	1		3.91	0.048	*	0.0097	no effect
Subjective Difficulty								
Main effects	*Relevant Lanes*	2		12.86	<0.001	*	0.082	medium
	Traffic Speed	1		8.13	0.005	*	0.026	small
	Gap Sizes	2		12.52	<0.001	*	0.080	medium
	Number of Vehicles	1		1.187	0.277		0.004	no effect
Two-way interaction	*Gap*Lane*	4		2.44	0.048	*	0.031	small
Four-way interaction	*Gap*Lane*Speed*Number*	3		3.25	0.022	*	0.031	small

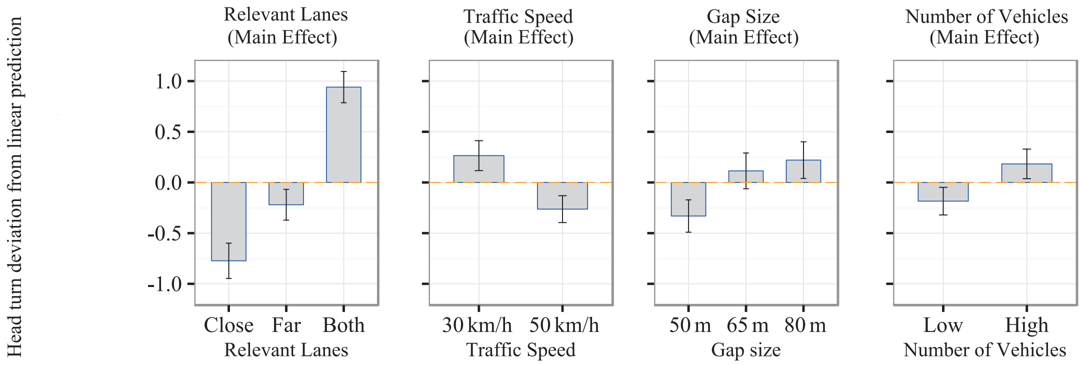


Figure 4.10: Results *Head Turns* for *Relevant Lanes*, *Traffic Speed*, *Gap Size* and *Number of Vehicles*. Image from Wagner et al. [199] © 2019 Elsevier.

The observed significant effects are illustrated in **Figure 4.9**. No significant effects were found for the *Gap Size* and *Number of Vehicles* factors.

Standardized Head Turn Count A four-way ANOVA was conducted for the SHT. The analysis yielded statistically significant ($p < 0.05$) main effects for all four factors and no significant interaction effects. The results parameters for the significant effects are reported in **Table 4.2**. It should be noted that the effect size is marginal for the *Number of Vehicles* with $\eta^2 \approx 0.0097$. The main effects are illustrated in **Figure 4.10**. **Table 4.2** and **Figure 4.10** do not include any interaction effects because no significant interaction effects were found.

Subjective Difficulty Estimation Another four-way ANOVA was conducted for the participants' subjective difficulty estimations. For the factors *Gap Size*, *Relevant Lanes*, and *Traffic Speed* statistically significant ($p < 0.05$) main effects were found. The results are presented in **Table 4.2** and all main effects are illustrated in **Figure 4.11**. One statistically significant two-way interaction was found for the factors *Gap Size* and *Relevant Lanes* (see **Table 4.2** and **Figure 4.12**).

The four-way interaction effect also returned statistical significance (see **Table 4.2**). Further investigation of this effect entails cross-comparison of all 36 *Factor Level* combinations. However, due to outliers and data exclusion, very little data is available for some of the 36 scenarios: no data exist for one of the scenarios and the data sets of six further scenarios include fewer than 5 data points each.

Therefore, it was assumed that a larger amount of data is necessary to be able to provide meaningful information about this effect. **Table 4.2** and **Figure 4.11** do not include any two- or three-way interaction effects because none of these effects reached statistical significance.

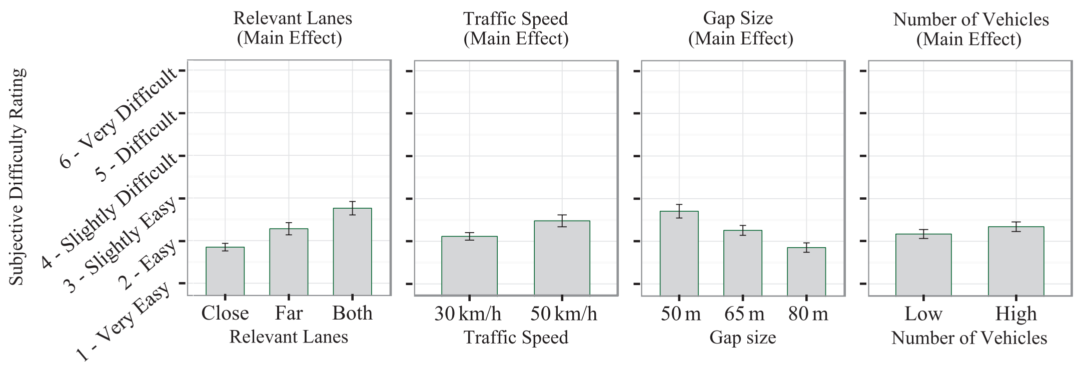


Figure 4.11: Results of *Subjective Difficulty* for *Relevant Lanes*, *Traffic Speed*, *Gap Size* and *Number of Vehicles*. Image from Wagner et al. [199] © 2019 Elsevier.

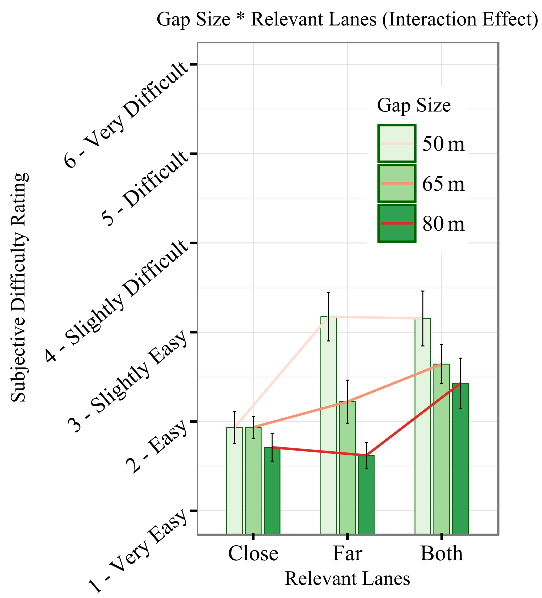


Figure 4.12: Results for the two-way interaction of the *Subjective Difficulty* between *Gap Size* and *Relevant Lanes*. Image from Wagner et al. [199] © 2019 Elsevier.

Post-Hoc Analysis of Gap Duration and Safety Margin

This section explains a post-hoc analysis regarding the influence of two timing parameters that was conducted after review of the main results presented above.

Objective and Scope The study revealed somewhat inconsistent results for the factors *Traffic Speed* and, particularly, *Gap Size*. As these two factors influence each other, their combination results in the actual time available for crossing, namely the time window in which there is a gap in the traffic. This time window is called *Gap Duration*

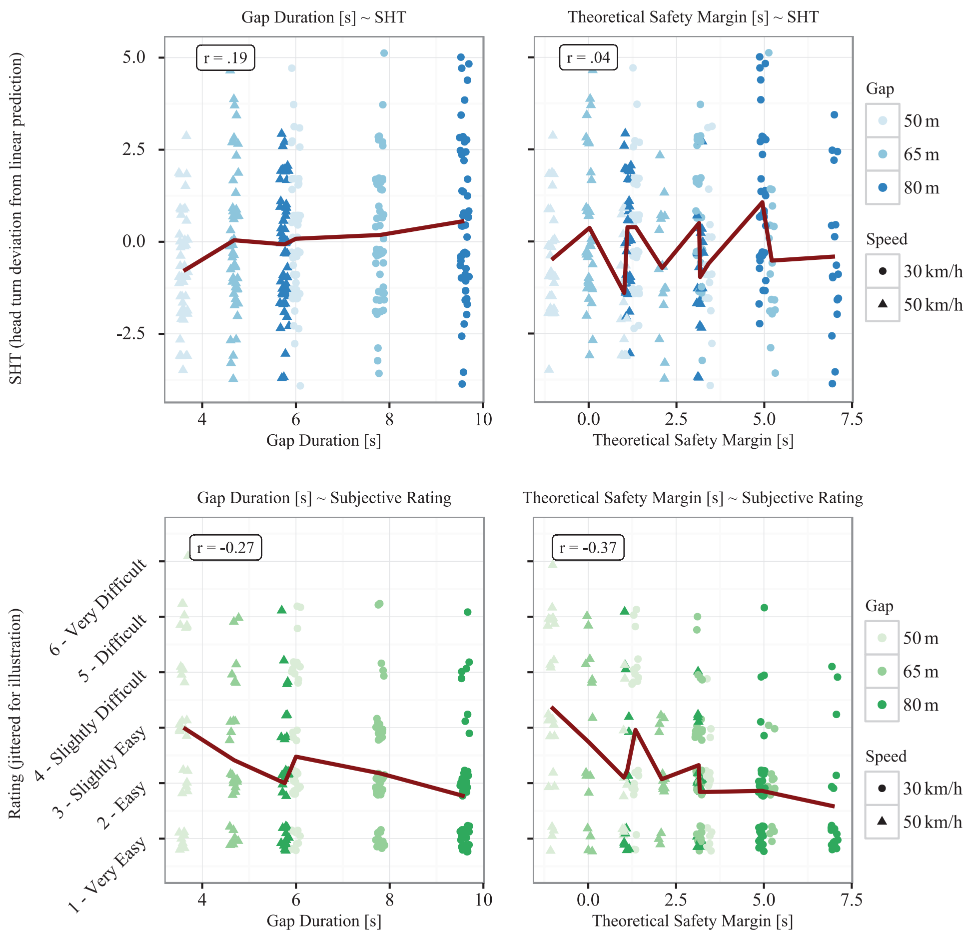


Figure 4.13: Results of the post-hoc analysis based on the *Gap Duration* and the *Theoretical Safety Margin* compared to the SHT and *Subjective Difficulty*. Image from Wagner et al. [199] © 2019 Elsevier.

in the following. This may have an impact on the difficulty of deciding if safe crossing within a certain gap is possible. Furthermore, the *Relevant Lanes* determine how far a pedestrian needs to walk to safety, i.e. how long the walk takes. When vehicles only approach on the *Close Lane*, this also means that the actual distance the avatar has to walk before it reaches the safe zone (in this case the far lane) is smaller than the distance when the vehicles drive on *Both Lanes*. This walking duration and the gap duration determine the *Theoretical Safety Margin*, i.e. 'how close' a crossing attempt would be. The *Theoretical Safety Margin* may also influence the difficulty of assessing if a safe crossing is possible. Therefore, a descriptive analysis was conducted to review how these continuous parameters relate to the continuous dependent variables (and difficulty indicators) SHT and *Subjective Difficulty* rating. It should be noted that detailed, inferential statistics would require further data.

Results The post-hoc results are illustrated in **Figure 4.13**. The SHT indicator slightly increases with growing *Gap Duration* (correlation coefficient: r=0.19); however, this increase seems too small (at a very high data variability) to be conclusive. No effect on SHT could be observed for the *Theoretical Safety Margin* (r=0.04), i.e. when walking duration is taken into consideration. *Subjective Difficulty* decreases with growing *Gap Duration* (r=-0.27) and *Theoretical Safety Margin* (r=-0.37). Further research is required to confirm these results.

4.3.4 Discussion

The results of the four factors are now discussed sorted according to their influence on the task difficulty:

Relevant Lanes: The *Relevant Lanes* factor yielded consistent results across all three difficulty indicators (dependent variables). There seems to be a clear difficulty ranking between the three conditions with traffic in the *Close Lane* representing the easiest condition. Traffic in the *Far Lane* scored more difficult in all three measures. In these trials, it is important to predict the walking trajectories further in the future and the zone with potential vehicle collision starts on the *Far Lane*, since the *Close Lane* is free. Both the human and the vehicle are further away from the potential collision zone at the time when the decision is made. This may be supported by one interpretation of the interaction effect between the *Relevant Lanes* and *Gap Size* factors in the subjective difficulty ratings: the differences between subjective difficulty ratings for different *Gap Sizes* are considerably stronger with traffic in the *Far Lane* than in trials with traffic in the *Close Lane* or in *Both Lanes*. As expected, the *Both Lanes* condition is the most difficult. The vehicles on *Both Lanes* must first be perceived and then their distance and the duration until they reach the crossing point must be estimated to decide if it is safe to cross the road or not.

The interaction effect between the *Relevant Lane* and *Gap Size* factors allows for two different interpretations. Firstly, the differences between subjective difficulty ratings for different *Gap Sizes* are considerably stronger with traffic in the *Far Lane* than in trials with traffic in the *Close Lane* or in *Both Lanes*. This may be due to the fact that trajectories have to be projected further into the future to determine if a collision will occur. On the other hand, *Gap Size* may have some impact on the subjectively perceived difficulty of different levels of the *Relevant Lanes* factor. For the small *Gap Size* of *50 m*, subjectively perceived difficulty seems to be low as long as traffic is limited to a single lane (no matter which one) and then increases when traffic occurs in *Both Lanes*. For the large *Gap Size* of *80 m*, difficulty seems to increase (and then plateau) as soon as there is traffic in the *Far Lane* (regardless of the *Close Lane*). The difficulty curve between *Relevant Lane* conditions is more monotonous for the medium *Gap Size* condition. This may be because this *Gap Size* may fall into the large *Gap Size* category for some participants and into the small *Gap Size* category for others. However, this is somewhat speculative. Which of these two explanations apply, as well as the detailed causal mechanics of this interaction, require further research.

Traffic Speed: The number of safety-relevant errors, i.e. unsafe crossings, was significantly higher with higher traffic speed. This aligns with the results of other studies which found that participants often had problems in correctly assessing speeds [207, 208, 210]. Similarly, participants perceived the decision to be more difficult when the cars were driving faster – even after exclusion of all trials in which the Unsafe Crossings occurred. However, SHT was lower when *Vehicle Speed* was high. As the post-hoc analysis already showed, especially the combination of *Traffic Speed* and *Gap Size* could be interesting, since these two factors together determine the *Gap Duration* and the *Theoretical Safety Margin*. The combined SHT results for the *Traffic Speed* factor and the *Gap Size* factor, as well as descriptive results from the post-hoc analysis, indicate that SHT may be higher as this time window grows. Based on the performed literature review, little research exists on the number of head turns, and thus visual attention allocation in pedestrian road crossing tasks needs to be investigated further.

Gap Size: The *Gap Size* factor yielded somewhat contradictory results across the three dependent variables. No effect was found on the number of safety-relevant errors. The SHT increased as the *Gap Size* increased. This may be due to the longer *Gap Duration*, although the cause for this cannot be determined conclusively from the collected data. However, participants experienced the trials to be easier for larger *Gap Sizes*. The post-hoc analysis suggests that this may also be the case for longer *Gap Duration*, since they are related. These two parameters cannot clearly be distinguished in the study. However, the inconclusive results do not qualify the *Gap Size* factor as a reliable difficulty manipulator.

Number of Vehicles: No relevant effects on the task difficulty could be found for the *Number of Vehicles* factor. A slight effect was found on the SHT; however, this effect explained less than 1 % of the overall variance ($\eta^2 \approx 0.0097$) and can therefore be neglected. The *Number of Vehicles* in a traffic scene does not seem to qualify as a reliable manipulator for traffic scenario difficulty.

Overall Scenario Difficulty: The study results suggest that *Traffic Lane(s)* and *Traffic Speed* may be good manipulators for the difficulty of virtual road crossing scenarios.

The inconsistent results of the *Gap Size* and the missing effects of the *Number of Vehicles* in the scene indicate that these factors may not be well-suited as difficulty manipulators. However, the SHT results for *Traffic Speed* and *Gap Size* and the results of the post-hoc analysis suggest a potential connection between the time window available for crossing and participants' visual attention allocation behavior. One potential explanation might be that the difficulty of the decision may be influenced by how close the time window is to the minimum time required to cross safely (which is also reflected in the post-hoc analysis). This may point at the *Theoretical Safety Margin* as another potentially useful difficulty manipulator which requires further investigation.

4.3.5 Conclusion

Implications for Rehabilitation Training Based on the results of the user study, various conclusions can be made regarding traffic factors that can be used to adjust the task difficulty for future cognitive rehabilitation applications (**RQ1**). The factors of the *Relevant Lanes* and the *Traffic Speed* have the greatest influence on the perceived task difficulty (most *Errors*, most *Head Turns*, and highest *Subjective Difficulty*). However, a clear influence of the *Gap Size* could not be shown. This confirms results from Oxley et al. [207] and Yannis et al. [208], who found that people pay more attention to *Gap Sizes* than *Traffic Speed*. Since more attention is paid to *Gap Sizes*, fewer mistakes are made. In a future study, it would probably be better to define *Gap Sizes* as a time window and not as a distance (i.e. *Gap Time*). At the same time, the neglected *Traffic Speed* causes more problems. The attention paid to the factors therefore varies, which leads to misjudgments in the factors that are not given much attention. The *Number of Vehicles*, on the other hand, showed no measurable difference. It neither led to a higher number of errors nor to a higher perceived difficulty. The participants only needed more head movements to make a decision. Head movement plays a major role especially for patients with visual impairments or unilateral spatial neglect. Due to a limited FoV, they need more time to search the entire environment and make a decision. This can lead to missed possibilities of crossing or to delayed reactions, so that the circumstances may have changed, which eventually results in an accident.

The *Number of Vehicles* can therefore be used as a tool to create variety between trials, but also to increase the difficulty for the mentioned patient groups. Further research on patients is needed to clarify this fact.

It is recommended to start with the lowest degree of difficulty of a corresponding rehabilitation application with only a few, very slow vehicles, which have a large vehicle distance and only drive on the *Close Lane*. For a training application the degree of difficulty should then be automatically increased or decreased after a series of correct/incorrect decisions. A similar strategy is realized in most systems for rehabilitation training with a level structure. Initially, only individual factors should be varied. Later, several factors should be changed at the same time. Since the data of this study was generated by testing healthy participants, the results need to be validated with impaired patients, since the results could be different for them.

Limitations The study has a couple of limitations. The environment could be even more realistic. The vehicles in the VE move at exactly the same speed in each scenario and only cars and no other vehicle types were used, e.g. motorcycles that could suddenly appear behind other vehicles and require a quick reaction, or electric/hybrid vehicles, which emit little or no noise and could be overlooked when relying on the sense of hearing. Furthermore, the virtual road is completely straight without any curve which leads to a easier overview and evaluation of the traffic situation. With today's VR headsets, the screen door effect still occurs due to the resolution and the close distance to the eyes. This limits the sharpness of distant objects, but it should have little influence on the recognition of the vehicles in the study. In addition, the relatively low FoV of the VR headset influences the overview in the VE. Depth perception in VEs can also have a different effect than in the real world, which is why deviations may also occur here that reduce the degree of reality [228]. Another limitation is that the evaluation of the *Difficulty Factors* was performed with healthy participants. The results with cognitively impaired people may differ from these and must therefore be investigated in the next step. However, the preliminary examination with healthy participants was an important prerequisite for initial feedback and for gaining experience with the system in order to subsequently improve it for use on patients. Most of these limitations lead to an easier road crossing than in reality. There are a couple of possibilities to improve the realism in the VE, e.g. adding other pedestrians, parking vehicles or a curved road. However, a more realistic world also leads to more difficult and complex tasks and may require more freedom in moving the virtual avatar, e.g. by adjusting the walking speed on the specific traffic situation.

4.4 Unilateral Spatial Neglect Assessment via VR Road Crossing

Before stroke patients can be treated specifically with various trainings, it is essential that a sufficient diagnosis is made in order to adapt the training to their needs. Conventional assessment methods have a problem with sensitivity [229] and are not able to address all USN symptoms in the chronic phase, since the patient has already learned various compensation techniques that disguise symptoms (recall Section 2.1.1). New methods for the assessment of USN are required. USN symptoms are especially easy to observe in everyday situations, as there are often many different stimuli present and the patient often needs longer to process them correctly or ignores them completely [122, 124, 125]. Computer-assisted assessment tools have many advantages over paper-and-pencil tests. The applications are usually easier to adapt for the therapist to the different needs of patients, completely controllable, can be easily repeated and the required output parameters can be recorded and assessed directly [7, 103, 230]. However, this high flexibility of rehabilitation programs is associated with a consider-

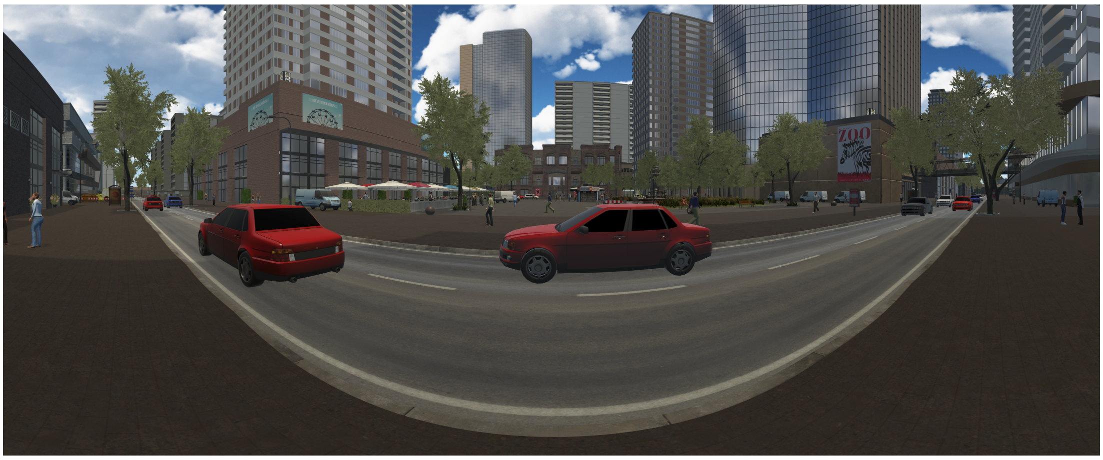


Figure 4.14: Panoramic image of the virtual road scene for neglect assessment.

ably higher development effort. VR offers the possibility to simulate ADL in a safe manner and can also reduce also the workload of medical staff, as it can be used by patients at least partially autonomously. Especially scenarios that are dangerous or difficult to perform in a real clinical environment can be realized in VR and open up many possibilities [7]. The scenario of safe road crossings represents a promising approach here that can be simulated with the help of VR. In cooperation with the Leipzig University Hospital, the existing application was developed further (recall Section 4.3) so that it can be used by stroke patients with the aim of diagnosing USN symptoms in the chronic phase. It was investigated whether stroke patients are able to use the VR application independently and without the occurrence of side effects (**RQ3**). In addition, parameters that can be used to distinguish stroke patients with and without USN were evaluated (**RQ2**).

In the following sections, first, the goals and requirements for the environment will be introduced. Second, the developed prototype and the decisions that were made during the conception phase will be presented in detail. The specific differences from the previous prototype are highlighted. Afterwards, the conducted study and their results will be reported and discussed. Here, the *Feasibility* (*Usability*, *VR Sickness* and *Sense of Presence*), *Potential Factors to Identify USN* and *Difficulty Factors* were evaluated with in total 18 stroke patients.

Parts of the texts and the results of the following section were already published in:

- **Sebastian Wagner**, J. Belger, B. Preim, and P. Saalfeld, "Crossing iVRoad: A VR for Detecting Unilateral Visuospatial Neglect in Poststroke Patients," in *Proceedings of the International Conference on Virtual Rehabilitation (ICVR)*, IEEE, 2019. [200]

- **Sebastian Wagner**, J. Belger, F. Joeres, A. Th¨one-Otto, C. Hansen, B. Preim, and P. Saalfeld, "iVRoad: Immersive Virtual Road Crossing as an Assessment Tool for Unilateral Spatial Neglect," *Computers & Graphics*, vol. 99, pp. 70–82, 2021. [201]

4.4.1 Requirements

For planning an assessment tool for USN, a number of requirements were first identified. These requirements have been extracted in an interdisciplinary co-operation of computer scientists, neuropsychologists and orthoptists who often work with neglect patients in clinical practice. Three major requirements were identified:

R1: Recording and Analyzing Behavior For a reliable assessment tool it is important that the behavior of the users is recorded in detail. The sequence of the tasks must be identical for all patients so that external influencing factors can be excluded and all data are based on the same basis.

R2: Cognitive and Physical Simplicity Since neglect patients often suffer from other stroke-related impairments such as hemiparesis and attention deficits, the interaction with the system should be designed as simple and robust as possible so that it can be used by as many patients as possible.

R3: Appropriate Level of Realism Since neglect patients have an impaired attention, they often have difficulty in distinguishing relevant and irrelevant stimuli in complex situations. It is important that the VE offers an appropriate level of realism so that the user has the feeling of being placed in the situation. Thus, realistic distractors should be integrated, as these also occur frequently in everyday life.

4.4.2 System

Since the developed application is an extension of the application from Section 4.3, it was also developed using the game engine *Unity* (version 2017.4.27f1). A variety of new assets mainly from the *Unity Asset Store* were used (e.g. buildings, human avatars, furniture). In this development stage, the application received the name iVRoad - *immersive Virtual Road*. In the following, the individual components of the VE are presented and set in relation with the presented requirements.

Scene

The entire scene was designed to be realistic and plausible so that the user can immerse themselves in the situation and the content can be compared to the real world (*R3*). After the environment of the first application was more suited to a residential area, an inner city scenario was chosen for further development, which consists of virtual roads to be crossed and a public square in between. This scenario seems more plausible with a high amount of traffic. Besides, an inner city scene gives much more possibilities to make the environment look busy and also distracting. For this, a scenario was designed that fits into the setting and gives meaning to the user's task. In contrast, to the first application the task is not just to cross a road multiple times. Instead in the system the user is supposed to perform a higher-level task, for which the road crossings are necessary. This can have an influence on the motivation of the user.

The chosen task was that the user wants to drop a letter into a mailbox on the user's way to work. To do so, the user first has to cross two roads and the square in between, and then return to the user's starting position to continue the way to work. This should be done as safely as possible.

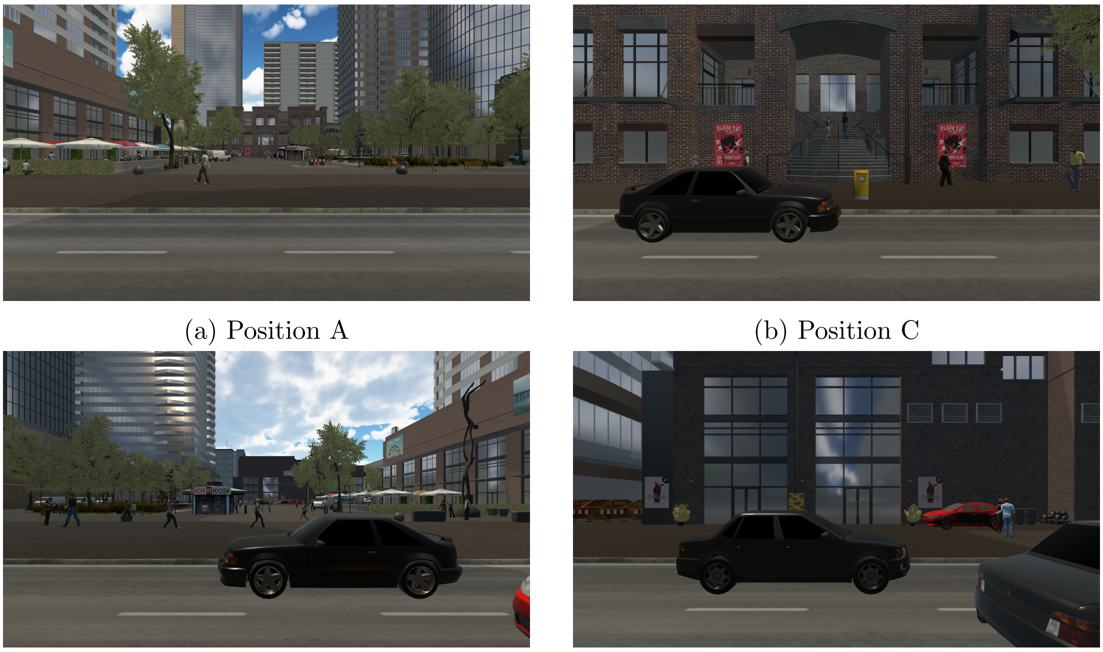
Two parallel 600 m long straight two-lane roads initially formed the basis of the scene. Subsequently, elements were added to the VE to create an authentic inner city scene (*R3*). **Figures 4.15–4.19** give an impression of the appearance of the VE. In the previous version of the application, distractors, such as pedestrians, were completely avoided so that the user could concentrate fully on the traffic. However, requirement 3 (*R3*) for the system is that the environment is as realistic as possible, also with regard to potential sources of distraction from the actual task. Patients with attention deficits may have particular difficulties in this respect. Several pedestrians were added sitting

Figure 4.15: Top view of the VE and the positions (from *A* to *H*) where the user is located within the task. The path to and from the mailbox is shown. At positions *A*, *C*, *E* and *G* the user should cross the road safely. The positions *B*, *D*, *F* and *H* are the goals of each crossing. At position *D* the mailbox is located where the letter is supposed to be dropped. Image from Wagner et al. [201] © 2021 Elsevier.

on park benches or standing in the surroundings. In addition to visual elements, the user is provided with sounds in the form of a constant background noise level typical for city areas and bird sounds.

The scenario that the user should first cross both roads towards the postbox and then return automatically leads to a change in the user's perspective on the scene. **Figure 4.15** gives an overview of the scene and relevant positions from a bird's eye view. **Figure 4.16** shows screenshots of the four positions where the roads should be crossed. As in the first application, the roads were 6 m wide (3 m per lane) and another 0.75 m had to be covered on the sidewalks, resulting in a total distance of 6.75 m.

Vehicles To simulate traffic, three car types were used, all with a very similar shape. These can have four colors (white, blue, red or black) and all have an identical vehicle length, but different shapes. The vehicle shape and color combinations used in the VE are randomized in the simulated traffic. As in the first application, it was decided against other vehicle types, as they can have an influence on the task difficulty.



(a) Position A

(b) Position C

(c) Position E

(d) Position G

Figure 4.16: Screenshots of the four positions where the road should be crossed. Image from Wagner et al. [201] © 2021 Elsevier.

Postbox Since the user's task is to successfully deliver a letter, there is a mailbox on the opposite side of the scene in front of the building (see position *D* in **Figure 4.15**). The position of this mailbox is changing. In half of the tasks, the mailbox appears to the right and in the other half to the left of the user (see **Figure 4.17**). Patients with left hemispheric neglect are likely to take longer to throw the letter into the mailbox on the left side. This is a subtask with a static target, whereas when crossing the road several moving vehicles must be watched.

Distractors Although some distractors, such as other pedestrians, had already been added to the scene in contrast to the previous application, the clinical partners indicated that the environment was still not distracting enough. More and also new distractors should be added. More pedestrians were added who move through the virtual world and interact with each other. *Auditory distractors* were also integrated. These include the barking of dogs, helicopter and tram sounds, honking vehicles, shattering glass and closing doors. This has contributed to a great extent to the realism of the scene (*R3*). This aspect is important for a reliable assessment tool, as it should represent an

Figure 4.17: The postbox placed at position D. The position of the postbox varies between left and right from the user (here left side). Image from Wagner et al. [201] © 2021 Elsevier.

everyday situation as good as possible, since USN symptoms can be observed frequently in everyday situations [124]. These distractors and the general complexity of the virtual world represent one of the major differences to the previous VE (recall Section 4.3.1).

Locomotion and Interaction

An important aspect is the locomotion and interaction with the system (recall Section 2.2.3). The interaction should be kept as simple as possible (*R2*). The most obvious method is the navigation in physical space and its transfer into the virtual space. This method represents the most realistic and natural form of locomotion, but it requires that the user can move safely. This is not always the case with stroke patients, who often suffer from hemiparesis or other physical limitations. In addition, this method has a high demand for free physical space (at least 7 m long). This cannot always be guaranteed in hospitals and other rehabilitation facilities.

As described in Section 2.2.3, a variety of locomotion techniques for VR are available. These have advantages and disadvantages. The navigation via joystick or control pad of a controller often leads to *VR Sickness* among users.

Teleportation would be particularly suitable for traveling large distances quickly. Furthermore, the risk for the occurrence of *VR Sickness* is quite low. However, this method is not suitable for crossing virtual roads, since this would make the task trivial, as the user could simply teleport to the other side of the road. *Walking-in-place* would have been a good compromise to reduce *VR Sickness* and to reduce the required interaction space. However, physically impaired patients should also be enabled to use the application (*R2*). Therefore, it was decided against real physical movement.

As in the previous application, indirect control of an avatar was applied again. The virtual avatar crosses the road, while the user is observing from a third-person perspective. This avatar is a representation of the user and crosses the road for them. This way, the user remains on the spot after making the decision to cross the road. Only after a successful crossing or a collision the user is automatically teleported to the other side of the road.

For the decision to cross the road, the user only needs to press the trigger button (*R2*) on the HTC Vive controller (simple interaction like in the virtual supermarket bye Mondellini et al. [118]). Once the user has decided to cross the road, it is no longer possible to stop the avatar. This is also necessary because otherwise the user could change the decision from a different perspective as they do not cross the road themselves and continues to stand at the roadside. Instead of the controller, the user sees a virtual rigid hand. This hand initially holds a letter and after it has been successfully delivered, the user sees an empty hand. To drop the letter in, it is necessary to move the virtual hand near the mailbox and then, as when crossing the road, simply press the trigger (*R2*). The position where the user should be in the physical space is marked by virtual footprints on the floor (see **Figure 4.18**). The position in physical space is the same at every position on the virtual road so that no movement is necessary after taking the correct position in the beginning.

After the letter has been successfully placed in the mailbox, the user is rotated 180 degrees in the scene (while the VR headset is faded out) so that they can continue without having to move physically (*R2*). Only one controller is required for interaction so that, depending on preference and existing restrictions, either the right or left hand can be selected for interaction. The head tracking enables the user to look around by turning the head and body.

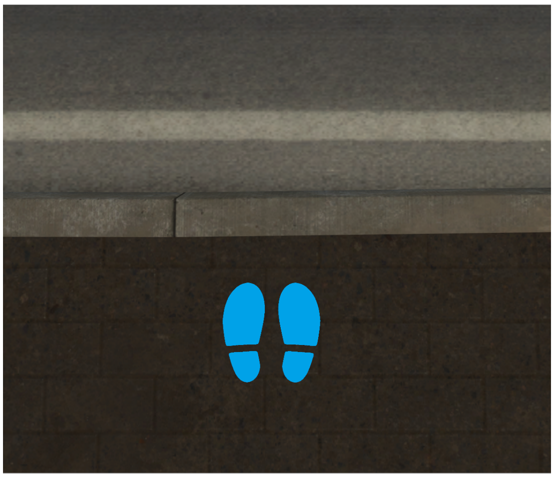


Figure 4.18: Footprints on the ground that indicate where the users should stand.

Another advantage is that the system can be used both sitting and standing. However, a sitting position usually makes it difficult to observe the road traffic, as it is not possible to look past most vehicles. To avoid this, the height of the user was recorded and for participants who preferred to perform the study in a sitting position, the system increases the user's height in the VE to their real height in a standing position. When the user was standing in the real world, the user's height is the same in the VE.

Avatar

The same ghost-like human avatar (see **Figure 4.19**) was used as in the previous application. This should enable identification with a human-like avatar and at the same time make clear that the user is not threatened by real consequences in the event of a virtual accident.

To assess the comparability between different users, the avatar speed was left at 1.45 m/s, as in the previous prototype. This comparability is especially important for an assessment tool. Based on the distance of 6.75 m that the avatar has to walk to cross the road, this results in a crossing time of 4.66 s.

As soon as the avatar has safely crossed the road or there is a collision with a car, the user is teleported to the other side of the road, while the VR headset is faded out. For this purpose, the image is briefly faded to make the transition as pleasant as possible. In addition, if there is an imminent collision between avatar and vehicle, the

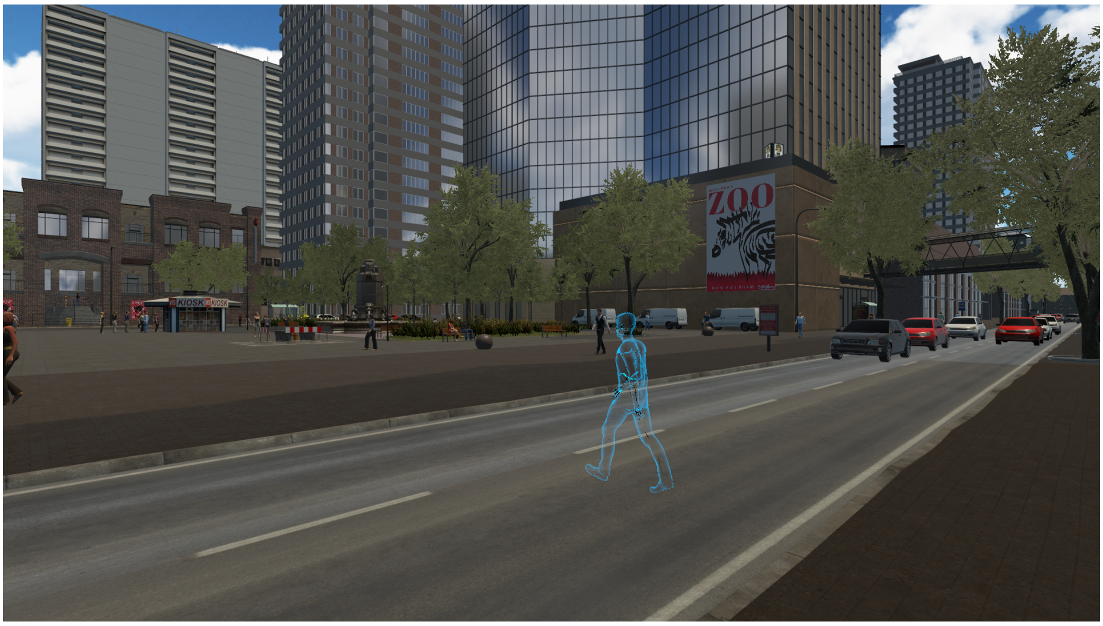


Figure 4.19: The virtual avatar is crossing the first road. Image from Wagner et al. [201] © 2021 Elsevier.

VR headset fades out before a collision would happen. Audio feedback is given by a positive or negative sound on correct or failed crossings.

Difficulty Factors

In order to make the tasks as diverse as possible and also ensure good comparability of the traffic scenario and the task difficulty, the results of the first study and related work were used. The parameters *Vehicle Speed* and *Traffic Direction* were found to be particularly suitable to adjust the task difficulty. Since no clear statement could be made about the parameter *Gap Size* in the first study, this parameter was used again in a modified variant.

The three selected *Difficulty Factors*:

- *Vehicle Speed*
- *Traffic Direction*
- *Gap Size*

Vehicle Speed The first factor is the *Vehicle Speed*. As in the first application, the two *Vehicle Speeds* of *30* and *50 km/h* were used again (recall Section 4.3.2). In these scenarios, all vehicles drive with the exact same speed (*30* or *50 km/h*).

Traffic Direction The second factor is the direction from which side the vehicles approach (*Traffic Direction*). Here, a distinction can be made between vehicles coming from only one direction (*Right* or *Left*), or traffic from *Both* directions. Other than the first prototype when vehicles only moved from one direction, only one lane was used, here, vehicles always move on both lanes. This means that the distance to be covered by the virtual avatar before it reaches the safe area is always the same. Especially patients with a left-sided neglect may experience large problems if they do not perceive vehicles correctly coming from the *Left*.

Gap Size The *Vehicle Speed* is directly related to the distance between the vehicles. The *Gap Size* must be large enough for a road to be crossed safely at all and must be correspondingly larger for vehicles moving at higher speeds. This is related to the *Theoretical Safety Margin* that came up during the post-hoc analysis in the study of the first application (recall Section 4.3.3). In the first developed application, *Gap Sizes* were defined in meters. Here, the *Vehicle Speed* directly influences the time the user has to pass a defined gap in meter (the faster the vehicles are, the faster a gap closes). Therefore, this time it was decided to use fixed *Gap Times* specified in seconds. To avoid confusion, *Gap Times* is again used as the term *Gap Size*. In the system, it should always be possible to cross the road safely so that the user can insert the letter into the mailbox and finish the task. To ensure this, the time needed to cross the road of 4.66 s was added together with the minimum safety distance to cross the road of 1.5 s. This results in a minimum required *Gap Size* of 6.16 s. In addition, a *Reaction Time* was considered, so the two *Gap Sizes* were defined at *6.5 s* and *7.5 s*. The *Reaction Time* here is the time between the opening of the traffic gap and the button being pressed to start the crossing.

Relevant Gaps These gaps of *6.5 s* and *7.5 s* will be referred to as *Relevant Gaps* in the following. The traffic between these gaps was filled with vehicles with a maximum gap of 2.5 s. However, pretests with patients have shown that the sizes of the *Relevant*

Table 4.3: *Difficulty Factors* and their levels. Table from Wagner et al. [201] © 2021 Elsevier.

Difficulty Factor	*Factor Level*
Traffic Direction	*Both*
	Left
	Right
Vehicle Speed	*30 km/h*
	50 km/h
Gap Sizes	*6.5 s*
	7.5 s
Traffic Variant	*Variant 1*
	Variant 2

Gaps are too large on their own and can be identified too easily. Therefore, it was decided to introduce so-called *Fake Gaps*.

Fake Gaps These are intended to provide variety in the scenarios, but at the same time challenge and lead the user to a correct assessment of the gaps that can and cannot be taken. For this purpose, it was decided on four different *Fake Gap* sizes: *3.5 s*, *4 s*, *4.5 s* and *5 s*. Three of these four *Fake Gaps* are not sufficient to cross at all (*3.5 s*, *4 s* and *4.5 s*), as the time is lower than the required crossing time of 4.66 s of the avatar, while one of these gaps is possible but not safe (*5 s*). This gap is intended to be particularly challenging and to determine whether the user is willing to make risky crossings. These four sizes of *Fake Gaps* were divided into two *Traffic Variants*, which are handled as a forth *Difficulty Factor*. *Variant 1* uses the *Fake Gaps* of *3.5 s* and *4.5 s*, while *Variant 2* uses the *Fake Gaps* of *4 s* and *5 s*. **Table 4.3** gives an overview of the characteristics of the factors. The combination of all factors results in 24 different traffic scenarios.

System Sequence

After iVRoad has been started, the user first finds themselves in an empty room where they can familiarize with VR technology and is supposed to go to the location marked by the virtual footprints on the ground. The user receives a series of instructions and then completes the integrated calibration process of the eye tracker. Afterwards, when the user is ready, they are teleported to the starting point in the virtual city and informed about the task and interaction possibilities with the help of instruction boards with explanations. In addition, the instructions were recorded with the help of a professional speaker and are presented to the participant, as patients with USN often have difficulty with reading (*R2*).

When the user is ready, they will first go through a tutorial session. The user crosses the roads in front of them and throws the virtual letter into a mailbox. The user is given step-by-step instructions on what to do and when. After the exercise was completed, the user proceeded through the 24 scenarios. The 24 tasks described above are divided into six task sets, each with four crossings (tasks) and the interaction with the mailbox. The order of these tasks is the same for all users (*R1*). The individual crossing tasks are structured such that two of the fake gaps are always presented first, followed by a relevant gap. This sequence is repeated a maximum of five times, while the order of the fake gaps alternates each time. If the user has not been able to cross the road by this time, two more fake gaps are presented, followed by a final ten second gap. This large gap should ensure that every user manages to cross the road. This can be important for the motivation of the user. However, if the user has not chosen this gap for crossing the road either, they will automatically be teleported to the next position.

Furthermore, the user has only one attempt to cross a road at a time. If the user decides to cross the road and this would result in a collision, the VR headset fades out before any collision with the avatar happens and the user is teleported to the other side of the road and the crossing is considered as an error. Thus, the goal was to minimize training effects, because for assessment applications it is important to reflect the current state of the patient in the best possible way. It was always ensured that the vehicles travel in the same direction on the roads on the user's way to and from the mailbox, in order to increase plausibility.

Therapist Control Panel

Since the patient is completely "isolated" in the VR headset and the therapist does not have a direct view of where the patient is currently located in the VE, a therapist control panel was integrated (see **Figure 4.20**). In this view the therapist sees live what the patient is currently seeing. This is the default view in a Unity standalone build. For VR applications, this also shows on the screen what the VR headset is currently displaying. UI elements have been added to this view (which only the therapist sees on the PC screen). These give the therapist the possibility to see which task the patient is currently in (top right of the screen). In addition, there are two control panels with buttons that allow the therapist to perform the initial configuration (start the eye tracking calibration, adjust the head height in VR if the patient wants to use the system in a sitting position). The therapist can also start and pause the individual tasks. At the bottom left of the control panel there is also a rectangle colored either green or red. This will turn green (correct position) or red (incorrect position) depending on whether the user is correctly positioned on the footprints shown in the VE. This is important because otherwise the user's perspective will be different from the intended position. In addition, a speaker icon is used here to symbolize when instructions are being conveyed to the patient by the system in the form of speech. Since the patient wears headphones, the therapist would otherwise not know when these are being played. In this way, it can be avoided that the therapist speaks during the instructions.

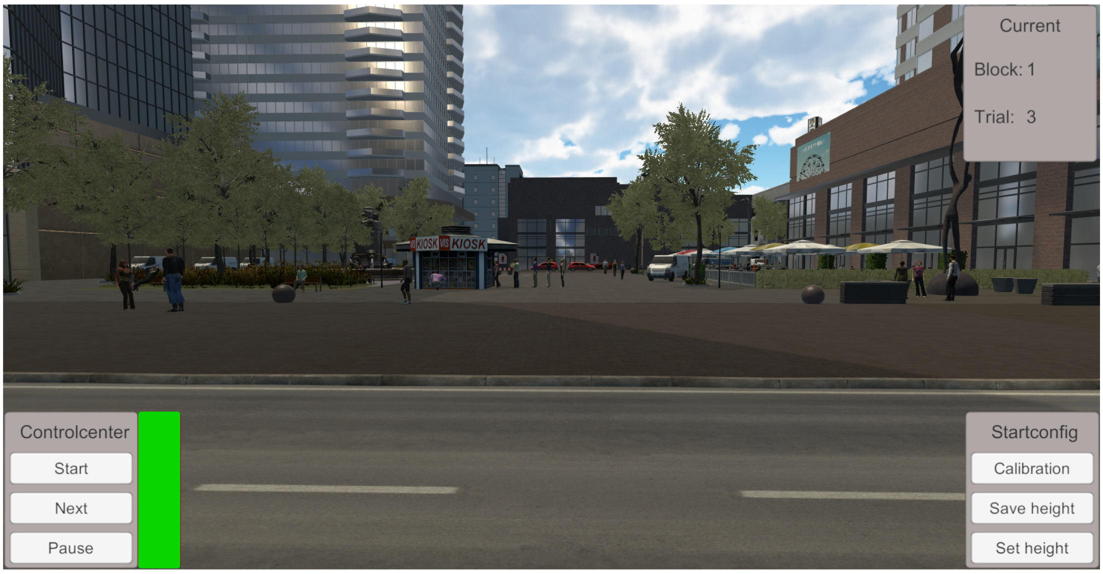


Figure 4.20: Screenshot of the therapist's view on the PC screen. The therapist can see what the patient sees in the VR headset, control the sequence of the system (bottom left and bottom right), see what task the patient is currently doing (top right) and whether the patient is standing correctly (green box bottom left).

Logging

It is very important to record data while the user is performing the tasks (*R1*). This includes primarily the performance data of the user, i.e. how often the user has crossed the road safely or unsafely, how many errors occurred, how many gaps they have waited for each time they crossed the road and how long the *Decision Time* was after opening a relevant gap, but also the time needed to insert the letter or the total task duration. In addition, head and eye orientation are permanently recorded using the orientation of the VR headset and the integrated eye tracker. These data allow for a detailed analysis of the user's exploration behavior, e.g. whether the left side has been neglected. However, the analysis of the eye tracking data is not part of this work and will be evaluated by the clinical partners. All this information is getting logged into two separate log files. The first log file stores the performance data and the second file head and eye orientations.

4.4.3 Study

This section describes the user study that was conducted. First, the objectives and the process of the study are explained, followed by the description of the participant groups, and finally the methods used to achieve the objectives are introduced.

Objectives

The study addresses two primary objectives and one secondary objective:

Primary Objective 1 - Feasibility The first objective of the study is to show that stroke patients are able to use the application without any limitations. This includes aspects such as occurrence of *VR Sickness*, *Sense of Presence*, and the *Usability*, especially the *Satisfaction* of using the application.

Primary Objective 2 - Exploration of Potential Factors to Identify USN The goal of the task is to be able to reliably distinguish between stroke patients with and without neglect based on certain parameters. The study will lay the foundation for this and identify possible factors in virtual road crossing that are promising for differentiation.

Table 4.4: Description of the two patient groups. One group with patients without diagnosed USN and one group with patients with diagnosed USN. Mean and standard deviation are given for age. Table from Wagner et al. [201] © 2021 Elsevier.

	no USN Group	*USN Group*
Age in years	55.11 (SD = 10.04)	60.78 (SD = 7.21)
Female (#)	4	3
Male (#)	5	6
Total (#)	9	9

Secondary Objective - Evaluation of Difficulty Factors Most studies on virtual road crossing refer to healthy participants. There are already a large number of studies with respect to which factors have an influence on problems with virtual road crossing [207, 208, 211, 212]. This has not been done for stroke patients, and only limited information on this is available. For this reason, in the study it will be investigated whether similar factors are responsible for task difficulty in stroke patients, as they are in healthy people.

Participants

A total of 18 subjects participated in the study. All of them suffered from the consequences of a stroke and were current or former patients of the University Hospital Leipzig. In all patients, the stroke had occurred at least six months ago. Thus, they were not acute patients. In nine subjects, no USN was detected in the diagnostic procedure (*no USN Group*). The other nine subjects were diagnosed with left-sided USN after stroke (*USN Group*). The characteristics of the two patient groups are shown in **Table 4.4**. The study was approved by the ethics committee of the Medical Faculty of the University Hospital Leipzig (Ethics code: 117/18-lk, March 5th, 2020).

Apparatus

A VR-ready notebook was used for the study and is equipped with an Intel i7-9700 processcor, a Nvidia Geforce RTX 2070 with 8 GB graphics card and 16 GB RAM. A HTC Vive Pro Eye VR headset was used. Their specification can be found in **Table 2.1** and it offers the possibility to do eye tracking. Due to the COVID-19 situation at the time of the study, patients were also required to wear a medical face mask throughout the study. As stated in Section 4.4.2, only one controller is needed to use the application.

Study Design

In the following, the methods that were used to address the objectives are presented.

Feasibility To address the first objective, only data from completed questionnaires is used. The *User Satisfaction Evaluation Questionnaire* (USEQ) [231], which was specifically developed for rehabilitation applications, was used to evaluate *Usability*, especially *Satisfaction*. This questionnaire consists of six questions (5-point Likert scale). To evaluate possible *VR Sickness* symptoms, the SSQ [76] was used. The SSQ consists of 16 items (4-point scale). Each item represents a possible occurring symptom of *VR Sickness*. In principle, this questionnaire is intended with healthy participants after using a system. However, since the participants are stroke patients who often suffer permanently from certain symptoms, it was decided to use the SSQ before and after using the system, to compare the SSQ values. Another question was, how much *Sense of Presence* is induced by the developed system? For this, the IPQ [84, 232, 233] with 14 items (7-point Likert scale) was used. The items result in four factors: *General Presence*, *Spatial Presence*, *Involvement*, and *Experienced Realism*.

Exploration of Potential Factors to Identify USN To identify the potential *Difficulty Factors* that could be used to distinguish the two groups of patients, the following three dependent variables were considered, which are commonly used in other studies [211, 222]:

- *Error Rate*
- *Decision Time* (elapsed time between task onset and start of road crossing by button press)
- *Head Direction Ratio* between the time patients looked left and right before making the decision to cross the road.

The two patient groups were compared with regard to these variables. The comparison was conducted for the overall trial set and for multiple subsets of trial conditions. The subsets were generated by splitting the overall trial sets by one *Difficulty Factor* at a time (e.g., the groups in all trials at *30 km/h* and the groups in all trials at *50 km/h* were compared and then this subset generation was repeated for the other *Difficulty Factors*). Comparisons were always made between the two groups of patients. This section is exploratory in nature to identify potentially relevant variables and conditions.

Evaluation of Difficulty Factors To address the secondary objective, the outcomes of the patient groups were investigated together. It was examined which of the *Difficulty Factors* influenced the dependent variables that were defined the most.

Experimental Procedure

At the beginning, the procedure of the experiment was described to the participants. Subsequently, the demographic data of the participants was recorded and a pre-questionnaire was filled out. Now, each participant went through the whole sequence in the VE described in Section 4.4.2. Previously, each participant had the choice whether to use the system in a sitting or standing position. Finally, the post-questionnaires were completed by each participant. The whole experiment took around 45-90 minutes per participant.

4.4.4 Results

A total of 432 virtual road crossings (24 per patient) were performed. Of these trials, nine had to be excluded due to too early crossing (before the first *Fake Gap*). In both groups, seven patients each preferred to use the system being seated, while only two patients per group wanted to complete the task while standing. 16 of the 18 patients stated that they had never used a VR headset before.

Feasibility

Usability The total scores of the USEQ evaluating the *Satisfaction* are shown in **Figure 4.21**. Both patient groups rated the system very high, with a total score of 25 out of

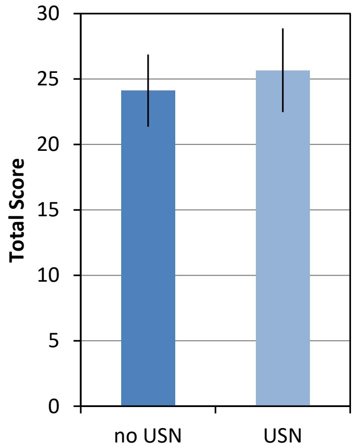


Figure 4.21: USEQ total score for both patient groups. The mean values and the standard deviation are shown. Image from Wagner et al. [201] © 2021 Elsevier.

30 maximum points. This value is consistent with the observations made by the study supervisor during testing that all patients were able to use the system without difficulty and also predominantly enjoyed using it. For mean values and standard deviations see **Table 4.5**.

Presence **Figure 4.22** shows the IPQ results for both patient groups. The *General Presence* is in a medium to high range for both groups. The *Spatial Presence* was rated highest overall. For *Involvement*, both groups are in a medium range. *Experienced Presence* was rated the lowest. For mean values and standard deviations see **Table 4.5**.

VR Sickness The results of the comparison of *VR Sickness* between pre and post in the sample, by using the SSQ, are shown in **Figure 4.23**. Positive values state an increase and negative values a decrease of an SSQ factor comparing the pre- and post-study. All mean scores are negative, meaning that, on average, all patients were less aware of their previously reported symptoms after using the system. The change in the *USN Group* is larger than in the *no USN Group* in all factors, however, the differences are very small. This indicates that the system did not cause any additional symptoms. *Nausea* symptoms decreased the least, whereas *Oculomotor* improved the most, and *Desorientation* values were intermediate. Accordingly, the *Total Score* was also in this range. For mean values and standard deviations see **Table 4.5**.

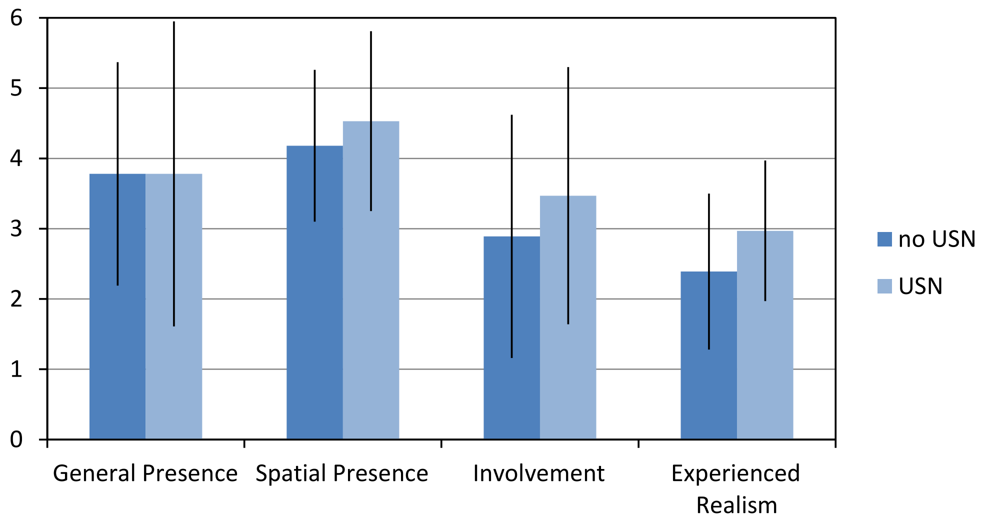


Figure 4.22: IPQ scores of both patient groups for the four factors *General Presence*, *Spatial Presence*, *Involvement*, and *Experienced Realism*. Image from Wagner et al. [201] © 2021 Elsevier.

Table 4.5: Mean values and standard deviations for the results of the questionnaires to evaluate the *Feasibilty* of the system. Table from Wagner et al. [201] © 2021 Elsevier.

	no USN Group		*USN Group*	
	M	SD	M	SD
Usability				
Total Score	24.11	2.76	25.67	3.20
Presence				
General Presence	3.78	1.59	3.78	2.17
Spatial Presence	4.18	1.08	4.53	1.28
Involvement	2.89	1.73	3.47	1.83
Experienced Presence	2.39	1.11	2.97	1.00
VR Sickness				
Nausea	-3.18	9.54	-5.30	6.93
Oculomotor	-6.74	9.62	-11.79	12.62
Desorientation	-4.64	12.06	-9.28	19.25
Total Score	-5.82	8.17	-10.39	11.77

Exploration of Potential Factors to Identify USN

To identify potential factors separating stroke patients with and without USN, Cohen's d effect sizes were calculated in general, and for each level of *Difficulty Factors* using

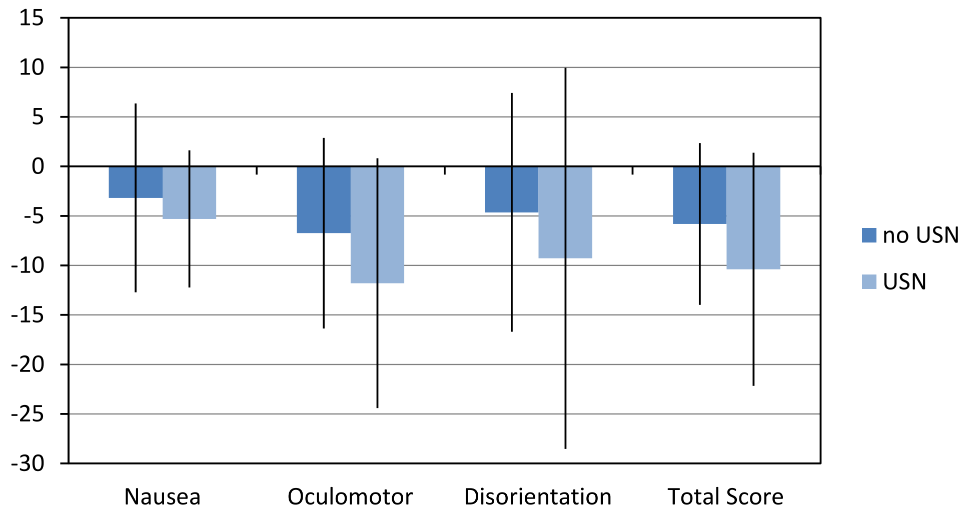
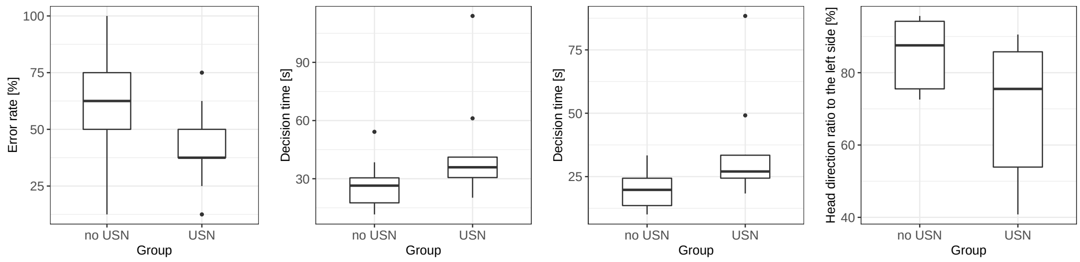


Figure 4.23: SSQ comparison scores for both patient groups. Positive values state an increase and negative values a decrease of an SSQ factor comparing the pre- and post-study. The mean values and the standard deviation are shown. Image from Wagner et al. [201] © 2021 Elsevier.

the three dependent variables *Error Rate*, *Decision Time*, and *Head Direction Ratio*. The results can be found in **Table 4.6**. For *Error Rate*, the difference between groups was particularly large for traffic from *Both* directions, with an effect size of d = 0.702. For *Decision Time*, larger differences were found in all conditions. The effect size across all conditions in terms of *Decision Time* was d = 0.791. The effect size for *Decision Time* was particularly large for trials with a *Vehicle Speed* of *50 km/h* (d = 0.960). For the *Head Rotation Ratio*, the difference was high for the trials where the *Traffic Direction* was from the *Left* side (d = 0.994). Boxplots for these four results are shown in **Figure 4.24**.

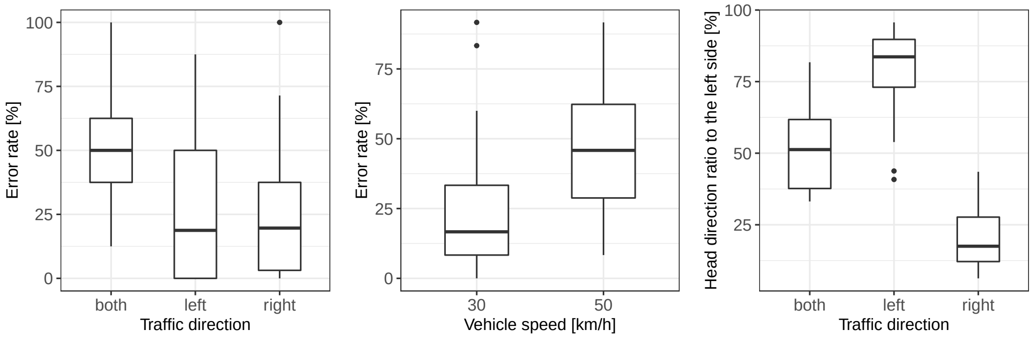
Evaluation of Difficulty Factors

To analyze the effect of *Difficulty Factors* on the dependent variables, ANOVAs were performed for all combinations. **Table 4.7** shows the statistical summary for the three conditions where the result became significant ($p < 0.05$). For *Error Rate*, significant differences were found among the *Difficulty Factors Traffic Direction* and *Vehicle Speed*. The effect size is f = 0.39 for *Traffic Direction* and f = 0.41 for *Vehicle Speed*. In addition, significant differences were found for *Traffic Direction* for *Head Direction*



(a) *Error Rate* for the trials with traffic from *Both* directions (b) *Decision Time* in all trials (c) *Decision Time* in the trials with *Vehicle Speed* of *50 km/h* (d) *Head Direction Ratio* to the left side in trials with traffic from the *Left* side

Figure 4.24: Boxplots for the conditions where the two groups differed to a large extent based on the dependent variables. Images (a), (b), (c) and (d) from Wagner et al. [201] © 2021 Elsevier.



(a) *Error Rates* for the *Traffic Directions* (b) *Error Rates* for the *Vehicle Speeds* (c) *Head Direction Ratio* for *Traffic Directions*

Figure 4.25: Boxplots for the traffic factors that resulted in a significant difference in the dependent variables. Images (a), (b) and (c) from Wagner et al. [201] © 2021 Elsevier.

Ratio with an effect size of f = 1.64. Boxplots for the three conditions are shown in **Figure 4.25**. All other conditions resulted in no significant differences.

4.4.5 Discussion

Feasibility (RQ3) All stroke patients who participated in the study were able to use the system without any difficulties. VR studies with stroke patients are still relatively rare in the literature. Patients in the acute phase would require special caution when using it. However, the strokes in the patients had occurred at least six months earlier.

Table 4.6: Effect sizes (Cohen's d) between the two patient groups for three dependent variables under the investigated trial conditions (based on the *Difficulty Factors*). The values of the *Difficulty Factors* for which the difference per dependent variable was particularly large are printed in bold. In addition, the difference in *Decision Time* was generally very high. See **Figure 4.24** for boxplots for these values. Table from Wagner et al. [201] © 2021 Elsevier.

	General	*Traffic Direction*			*Vehicle Speed*		*Gap Size*		*Traffic Variant*	
		both	*left*	*right*	*30 km/h*	*50 km/h*	*6.5 s*	*7.5 s*	*Variant 1*	*Variant 2*
Error Rate	0.105	**0.702**	0.337	0.027	0.045	0.266	0.097	0.081	0.338	0.186
Decision Time	**0.791**	0.827	0.601	0.711	0.652	**0.960**	0.762	0.782	0.808	0.730
Head Direction Ratio	0.421	0.146	**0.994**	0.383	0.317	0.481	0.436	0.386	0.207	0.561

no effect: d < 0.2; small effect size: 0.2 <= d < 0.5; medium effect size: 0.5 <= d < 0.8; large effect size: d >= 0.8 [234]

Table 4.7: Summary of the statistical results of the ANOVAs and the effect sizes for the *Difficulty Factors*. Only statistically significant results are shown. Table from Wagner et al. [201].

Dependent Variable	*Difficulty Factor*	dF	F	p	η^2	f
Error Rate	*Traffic Direction*	2	3.845	0.028*	0.131	0.39
	Vehicle Speed	1	5.858	0.021*	0.147	0.41
Head Direction Ratio	*Traffic Direction*	2	68.370	<0.001*	0.728	1.64

no effect: f < 0.1; small effect size: 0.1 <= f < 0.25; medium effect size: 0.25 <= f < 0.4; large effect size: f >= 0.4 [234]

Thus, it was demonstrated that patients in this stage are able to perform complex tasks in a VE. Due to the simple and intuitive interaction of the system, high results in *Usability* could be achieved.

Using the SSQ, it was shown that the system, with its simple interaction and lack of navigation in the VE, does not induce *VR Sickness* in stroke patients. In fact, improvements in all dimensions of the SSQ were observed. These improved scores probably mainly come from the fact that patients were distracted from their symptoms by using the system. This effect is also exploited in pain therapy using VR. Here, VEs usually serve to distract the patient from a painful examination/therapy [178, 182].

The overall *Sense of Presence* was rated medium to good. No major differences are apparent between the groups, but the *USN Group* scored slightly above the *no USN Group* on three factors. Reasons for the rather mediocre presence values could be the very limited operation and the few freedoms of the system. The users have no possibility to explore the VE themselves and are completely guided through the environment. The virtual avatar could also have led to the reduction of the *Sense of Presence*. This avatar has mainly been used to protect against the possible occurrence of *VR Sickness* symptoms. In addition, this form of virtual road crossing also allows patients with, for example, limitations in real locomotion to use the system. Therefore, for the performed study these positive aspects outweigh the disadvantages in the *Sense of Presence*. More varied scenarios and environments can also lead to an increase in the *Sense of Presence*.

Exploration of Potential Factors to Identify USN (RQ2) Potential factors to separate stroke patients with and without USN were identified. In particular, differences in *Decision Time* were highly apparent in all conditions. This could indicate that patients with USN needed more time to process a traffic situation and accordingly took longer to make a decision. This makes sense, since information processing is generally slowed down in neglect patients.

The *Error Rate* differed especially in traffic from *Both* directions. This is due to the severe attentional deficits of USN patients, as vehicles coming from *Both* directions have a particularly high cognitive workload. However, the total number of errors did not differ between the two groups. Here, it would have to be verified again with the help of healthy participants whether this is due to the general task difficulty or whether the attention deficits are also so pronounced in the patients without USN that they have difficulties with such a task.

Fine-tuning the difficulty level might be necessary accordingly. A particularly large difference was shown in the *Head Direction Ratio* for *Traffic Direction* coming from the *Left*. Since the patients with USN have a left-sided USN, this was an expected result, since these patients have particular difficulties recognizing and responding to stimuli on the left side. A comparable tendency would be expected with right-sided USN, except that these patients would have difficulty with vehicles approaching from the *Right* side. However, what was unusual here was that the USN patients did not make more errors with traffic coming from the *Left* side. This could indicate that the other *Difficulty Factors* have a greater impact on the task difficulty.

Evaluation of Difficulty Factors (RQ1) Especially the *Traffic Direction* and the *Vehicle Speed* had a great influence on the *Error Rate* and thus the difficulty of the road crossings in the conducted study. The conditions *Gap Size* and *Traffic Variant* are negligible in terms of difficulty. These observations are consistent with the results of previous studies with healthy participants [199, 207, 211, 212]. In particular elderly people have difficulties in assessing vehicles in the second lane [212]. The result that the *Head Direction Ratio* differs greatly among the different *Traffic Directions* is to be considered rather trivial, whereas the analysis of potential factors separating the patient group showed that large differences are visible here between the groups, especially for traffic from the *Left*. Therefore, a separate consideration of the *Difficulty Factors* in relation to the two groups could be useful.

4.4.6 Conclusion

An assessment tool for USN was presented and tested on a total of 18 stroke patients with and without USN. Potential parameters and conditions that are particularly useful for distinguishing patients with and without USN were identified (**RQ2**).

The factor *Decision Time* has been identified as a very good measure. *Error Rate* and *Head Direction Ratio* also turned out to be reliable measures of separation, especially considering the *Traffic Direction*. It was also shown that the stroke patients in the study had problems in estimating speeds and when traffic was coming from *Both* directions.

This is consistent with other studies conducted with healthy participants. This was the first study of virtual road crossing with modern VR hardware with stroke patients. Previous work that tested stroke patients using virtual road crossing systems [128, 129, 223] did not use modern VR headsets (like HTC Vive or Oculus Rift). This modern VR technology has various advantages over older VR headsets or desktop-based systems, such as a better visual quality and more natural interaction to improve the *Sense of Presence*.

The developed system could be used without difficulties by all patients in the study and no side effects occured (**RQ3**). Quite the contrary, the system seemed to have a relaxing and especially distracting effect on the patients, as discomfort that existed before system use seemed to be less present after use.

The work has a number of limitations. The system offers limited freedom to the patient. All vehicles in the scenarios travel at either *30* or *50 km/h*. In real road traffic, the speed of vehicles would be more varied. Here, the degree of realism could be increased. Another limitation is the fixed movement speed of the avatar. A better alternative would be to employ the user's real walking speed. However, this would make it difficult to compare between users.

The data for the potential factors to distinguish patient groups need further investigation. In an assessment tool, the goal is to diagnose a patient based only on the results. This requires fixed ranges of measurements under which a patient can receive an appropriate diagnosis. This may also require comparisons to other existing USN assessment tools.

In the country in which the study was conducted, right-hand traffic is common. For countries with left-hand traffic, the *Traffic Direction* would need to be adjusted in the condition with vehicles from *Both* directions. In the study, only patients with left-sided neglect (50 % of right-sided brain damage) were tested, because it is much more common in the consequence of a stroke attack than right-sided neglect (30 % of left-sided brain damage) [235]. However, it can be assumed that right-sided neglect could be detected in the same way. Difficulties in responding to stimuli on the right side are to be expected. However, especially for the variant with traffic from *Both* directions at the same time it would have to be reconsidered whether it makes a difference, since vehicles coming from the right drive in the far lane, and since elderly people already neglect the far lane more often anyway. For *Traffic Directions* from the *Left* only and from the *Right* only, opposite results to left-sided neglect are expected.

Although the possible FoV in modern VR headsets is already much higher than in earlier systems, it is still lower than the FoV of a healthy person in reality. This can affect the result compared to real tasks, especially for tasks where peripheral vision is an advantage. Therefore, the presented task can greatly benefit from the technological progress by increasing the FoV and improving the transferability to real road crossings. Since the patients had to wear a medical face mask during the entire study, the displays of the VR headset frequently mist up and had to be cleaned in between if necessary. This could had an influence on the visual quality.

4.5 Summary

This chapter presented the development and evaluation of a virtual road crossing task using a VR headset for stroke patients with USN. First, the underlying decision-making process for the selected scenario was presented. Then, related work from the field of traffic psychology on road crossing, especially in the context of virtual road crossing, and also existing work for the assessment and training of stroke patients with USN was presented.

Since it is important for an assessment/training tool to be able to determine an adequate level of difficulty, the topic of *Difficulty Factors* in virtual road crossings was first examined in detail (**RQ1**). For this purpose, a virtual road scene was first developed, consisting of a straight two-lane road in a fictitious urban residential area. A fully furnished VE was designed, however, without pedestrians or other factors distracting from the task. The purpose was to ensure that the participants in the study could fully concentrate on the presented tasks. Since the system was later designed to be used by stroke patients, who often have various motor impairments, care was taken to simplify the interaction. Therefore, the user could trigger the crossing of the road by pressing a single button. When this was done, a virtual avatar representing the user started crossing the road. Thus, no physical movement in reality was required of the user. In the conducted study, the participants' task was to assess whether it was safe to cross the road or not in given situations. In total, there were 36 different traffic scenarios, which consisted of a combination of the four factors *Vehicle Speed*, *Traffic Direction*, *Gap Size* and *Number of Vehicles*. Each subject went through six out of these 36 scenarios. A total of 60 healthy participants between the ages of 16 and 79 participated in the study. For evaluation purposes, measured values were recorded by the system (*Error Rate* and *Head Turns*) and additionally the perceived *Subjective Difficulty* was requested on a 6-point Likert scale. The results of the study showed that especially the factors *Vehicle Speed* and *Gap Size* had a great influence on the *Subjective Difficulty* of the task and also on the performance data. For the *Gap Size* factor, no clear results could be found in the dependent variables. The *Number of Vehicles* factor was identified as an insufficient factor to adjust for task difficulty (**RQ1**).

Based on the system and the results of the first study, the existing system was further developed and subsequently evaluated in cooperation with neuropsychologists from the University Hospital Leipzig. The system was designed and developed with the goal of assessing USN in stroke patients. The VE was completely redesigned to achieve the set goal and was named iVRoad. The setting of the second system was a fictitious busy inner city scene with two two-lane roads, which has a variety of visual and auditory distractors. These distractors turned out to be particularly important, since especially patients with USN have difficulties to focus their attention when many stimuli with a high distraction potential are available. Due to the planned use on patients, it was particularly important to ensure that as many patients as possible are able to safely interact with the system. Therefore, the simple interaction was carried over from the first version of the system, which meant that no physical movement of the user was required to move around the VE. Additionally, the ability for the system to be used while seated or standing was included.

A user study of 18 stroke patients (nine with and nine without USN) was conducted to investigate *Feasibility* (**RQ3**). Furthermore, factors that might be suitable for the identification of USN in stroke patients were investigated (**RQ2**). In addition, as in the first study, the *Difficulty Factors* were examined to provide an indication of whether the results of patients were comparable to those of healthy participants (**RQ1**). As in the first study, different traffic scenarios were designed, which this time consisted of the factors *Vehicle Speed*, *Traffic Direction*, *Gap Size* and *Traffic Variant*. This resulted in 24 scenarios. Each of the participants went through all scenarios once in the study. Various questionnaires were used to evaluate the *Feasibility*. All patients were fully able to successfully interact with the developed system. For the evaluation of *Difficulty Factors* and appropriate measures to distinguish between patients with and without

USN, the dependent variables *Error Rate*, *Decision Time*, and *Head Direction Ratio* were examined. *Decision Time* turned out to be a particularly promising measure, as it showed differences across all traffic scenarios (**RQ2**). For the measure *Error Rate*, differences were found especially for the condition with traffic from *Both* directions. As with the healthy subjects in the first study, the factors *Traffic Direction* and *Vehicle Speed* turned out to be particularly important for the task difficulty (**RQ1**).

4.6 Future Work & Outlook

The last section of this chapter will give an overview of potential for future work to further improve the current system with a large variety of new functionalities.

Assessment of Patients with USN The clinical partners of the University Hospital Leipzig have continued the data collection with patients. With a larger data base, they want to define precise threshold values for the identified factors and also investigate clinical outcome parameters to be able to clearly distinguish between patient groups. In addition, it will be used for initial diagnostic alignment, as the results so far have been so promising and helpful. Furthermore, the partners want to investigate the eye tracking data in detail to gain even more insight into patient behavior.

Training of Patients with USN Further, the knowledge gained can be used to develop a training system for stroke patients with USN. In this case, patients could work with the system over a longer period of time and, for example, learn compensation techniques for safe road crossing and improve their overall attention. However, this would require a larger variety of scenarios and VEs (e.g. crosswalks, traffic lights, more complex road networks, road crossing at night) to keep patients motivated (see **Figure 4.26**). However, these new aspects would also have an impact on task difficulty and would need to be investigated for their influence. Integrating gamification elements or even linking the road crossing task to other activities, such as a virtual shopping trip to the supermarket, can help to give the patient a stronger *sense of purpose* in the task and can lead to a better transfer to daily life. It is particularly interesting whether this training enables a sustainable transfer into daily life, i.e., whether the patients' attention improves and also if they can perform road crossings more safely and consciously. This would also require the precise elaboration of a difficulty level structure. There, the knowledge gained from the studies conducted on traffic factors and their influence on the task difficulty can be used and combined with new traffic scenarios, such as non-linear road alignments.

Figure 4.26: VE at night from the system developed in Section 4.3 as a potential variation of a traffic scenario to improve the variety and adjust the task difficulty.

Assistance Features In such a training system, it is also possible to integrate assistance features to support the patient, e.g. a reference object like a road sign on the affected side, and instruct the patient to move their view until they see the sign. This could be especially useful in the beginning, when patients are new to the system and have severe USN symptoms. Hagiwara et al. [236] used such technique for patients with allocentric neglect (recall Section 2.1.1). In this work, a visual cue was used to guide the attention of USN patients to their neglected side in VR. Also optokinetic stimulation could have a benefit. The idea is to present visual stimuli which constantly move from the healthy to the neglected side. Studies have shown that patients pay more attention to the neglected side [29]. Here, the possibility of use and the effectiveness for virtual road crossings could be investigated.

Replay Function Since patients with USN are often not aware of their impairment, a replay function that allows the patient to view their behavior while using the system would be useful. This allows therapists to point out the behavior to the patient to discuss possible improvements. This is already done by the clinical partners using recorded videos. However, a proper replay function would bring further possibilities and not just the plain playback. It would be possible to quickly navigate between tasks, to view the situation from different perspectives (e.g. to show the patient what they did not pay attention to) or even to directly jump into a task to repeat it. This could be solved with a timeline on which each task is marked. Furthermore, the therapist could be given the possibility to add own markings/annotations. The basis for the implementation of such a function are complete behavioral data of the patient during the use (button presses, head orientation and gaze direction). This data is already collected by the implemented system and could be added to such a replay system afterwards. In addition, this replay function could also be used for study purposes in order to analyze the behavior of the users post-hoc once again in more detail. This way, further performance data could also be collected retrospectively using the data already recorded. This would greatly increase the variety of possibilities of use offered by the system to the therapists.

Therapist Configuration Panel In Section 4.4.2, a control panel for the therapist has already been presented. This could be further expanded, as this control panel was specifically designed for the conducted study. Further setting options would be required for a training system. For example, a possibility to select certain scenarios, a certain level of difficulty, or to turn assistance features on or off would be conceivable. In addition, the therapist could be given several views for observing the active scene. Besides the direct view of what the patient is currently seeing, the therapist could be provided with more information (e.g. bird's eye view). Similar to the system of Rizzo et al. [186] (recall Section 3.3) for the treatment of PTSD in Iraq vetarans, the therapist could be given the possibility to directly intervene in the scene via such an interface and, e.g., start specific distracting stimuli. Likewise, an easily accessible editor for scenarios could be integrated into the system, which would allow the therapist to easily create their own customized scenarios.

Since the interaction possibilities are limited when the patient is wearing the VR headset, it would also be conceivable to enable the therapist to join the patient in the VE. As soon as the therapist enters the VE, interaction between therapist and patient is possible again. Therefore, it is necessary to think about a suitable representation of the therapist in VR and which interaction possibilities the therapist should have.

Feedback & Performance Visualization Another important aspect for both assessment and training is the evaluation of the measured data and its visualization. At the end of an assessment session, it would be desirable to perform a direct evaluation of the performed session in an automated way and to visualize suitable information. This can be important for the therapist, but also for the patient to assess the performance. Depending on whether the visualization is to be used for the therapist or the patient, its complexity can and must differ, as the information should be presented in a way that is easy to understand for patients. The therapist could be given more complex evaluation options. Evaluation parameters could be the error rate, number of safe/unsafe crossings, training time and *Head Direction*/gaze analysis. In a training program, it would also be necessary to not only show the data from the current session. The data should be put in context with the previous sessions to analyze possible trends. See **Figure 4.27** for an idea for a visualization of the *Head Direction* data that could easily show a lack of attention to one side.

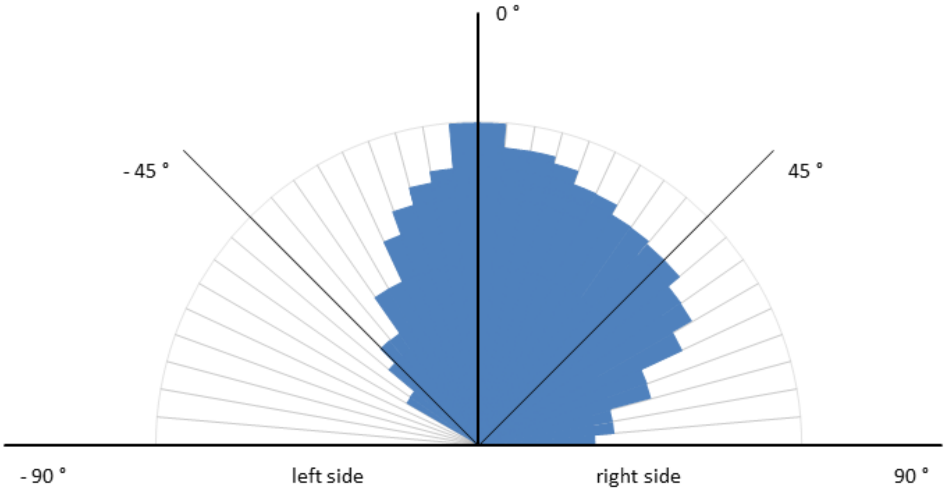


Figure 4.27: An idea to display the data of the *Head Direction* in which the patient looked during a task or the whole session. The duration of the head direction is displayed in 5 degree steps in the form of a radial histogram (positive degree values used for *Head Direction* to the right and negative values to the left). The 0 degree line shows the user's view when they look straight ahead. The diagram is not based on real patient data, but is only meant to show a possible direction for a visualization. This example shows how it could look like when less attention was given to the left side.

5 Acrophobia Virtual Reality Exposure Therapy

Within this thesis, the topic of VRET was also addressed, since there are many similarities between the development of a system for the rehabilitation of stroke patients and the therapy of patients with anxiety disorders, and both can benefit from each other. For both types of therapy, it is of great importance that patients use the systems over a longer period of time in order to achieve therapeutic success. This depends to a large extent on the patient's attitude and motivation. The therapist, but also the therapy tools they use, such as a VRET application, can contribute significantly to the patient's motivation. Task difficulty is an important factor in this context. A system for the treatment of people with acrophobia was developed by Kay Illner within his master thesis [237], and was published together [238]. A VRET application can improve the accessibility of ET for patients. Hereby, transferring the mechanisms of real-life ET is essential to create an effective application. This is the great strength of VRET, because any real situation can be simulated and the VE can also be extended by elements that would not be feasible in the real world. Many studies have already successfully demonstrated the applicability of VRET for the treatment of anxiety disorders (recall Section 3.2).

Two VR scenarios were developed which shall induce fear of heights, with various parameters to adjust the VE and possibilities for easy extension of these scenarios. These parameters allow to adjust the task difficulty (**RQ1**). Our system allows the direct report of current anxiety values so that they can be analyzed after exposure. In addition, various motivational elements were integrated to support the user during therapy. At the end of this chapter, an outlook to possible studies that could be conducted with the help of the developed application is given and discussed.

Parts of the texts and the results of the following section were already published in:

- **Sebastian Wagner**, K. Illner, M. Weber, B. Preim, and P. Saalfeld, "VR Acrophobia Treatment-Development of Customizable Acrophobia Inducing Scenarios.," in *Proceedings of Workshop on Visual Computing for Biology and Medicine (VCBM)*, pp. 49–53, 2020. [238]

5.1 Requirements

In order to define requirements for such an application, previous literature (recall Section 3.2) was reviewed and semi-structured interviews with two experienced therapists were conducted. Both therapists had several years of experience in conducting ET, including patients with acrophobia. However, they had no prior practical experience with regard to VRET. They were familiar with the concept, and were very interested in learning more about the topic and gaining experience. The main goals were to get practical insights not evident from studying literature and to get early feedback on specific ideas and directions for the prototype. In the following, the interview process, results and conclusions for the prototype are explained.

Interview Process The interviews began with questions about the therapist's current therapeutic approaches and specifically about experiences with ET. In particular, questions were asked about the necessary preparations and the procedure of the ET session. In addition, the interviewed therapist was asked to elaborate on aspects that they personally consider to be particularly important in ET. The interviewer was asked about current potential for improvement and where limitations/problems exist. Based on this, the interview was directed towards VRET to inquire about previous experiences with the topic. Subsequently, it was possible to talk specifically about whether any disadvantages or problems could be eliminated with the help of VRET. Finally, concrete aspects for the development of a prototype were discussed.

Interview Results and Discussion Both therapists mentioned high buildings and towers as suitable locations for in-vivo ET. Parking garages were also mentioned as particularly suitable, as they offer special exposure potential due to their multiple floors and open view to the outside.

A suitable method for locomotion in VR should be chosen carefully. Sudden fast movements run the risk of bringing the patient into critical situations without control and should be avoided. Also, surprises should generally be avoided to keep the trust of patients, which is required for successful therapy.

The experts expressed concerns mainly in terms of the VR headset isolating the patient, as they wondered how they would support the patient if they could not see what the patient was seeing. However, these concerns could be addressed by displaying what the patient sees on the PC screen. They also noted that ET or VRET can only be helpful if the challenge is severe enough for the patient. Both therapists were asked about how high they would rate the minimum requirement in terms of anxiety level (on a scale of 1 to 9). One therapist answered that the anxiety level should not be below 5 in the patient. The second therapist estimated it even significantly higher. Her opinion was that it should not be below 8. In this regard, she suggested a starting level of exposure at a minimum of 15 m. In order to be able to estimate how much anxiety the patient feels during ET, patients are regularly asked about their current anxiety level during the session. Thus, it would be very helpful if the system would do this automatically and save the data at the same time. Therapy sessions do not have a fixed time limit and need to be adapted to the individual patient. Therapy progress should be presented to the patient and show them the achievements already made to motivate them.

The derived requirements are listed in the following:

R1: Appropriate Scenarios Appropriate scenarios must be developed that induce sufficient anxiety in the patient and also allow for a gradual increase in difficulty.

R2: Suitable Locomotion Technique A locomotion technique should be used that allows gradual exposure and does not cause abrupt movements that unexpectedly place the patient in an uncomfortable situation.

R3: Anxiety Reporting Function An anxiety reporting function would assist the therapist in assessing how much anxiety the patient is currently feeling. Recording these measurements would also allow a post-hoc analysis of the data.

R4: Increase Motivation/Visualize Therapy Progress Keeping patients aware of the progress they have already made can increase their motivation and reduce the likelihood of them dropping out of therapy, as well as the usage of motivational elements.

5.2 System

This section describes the VE that was created based on the current literature and the conducted interviews with the two therapists. A tutorial scenario and two exposition scenarios were developed and are described in the following. Since it is very important in ET to approach the stimulus gradually, appropriate locomotion techniques are discussed. A system for easy reporting of current anxiety measures during exposure and motivational elements will also be presented. Like the applications in Chapter 4, the VRET application was also developed using the game engine Unity. As a VR headset, the Oculus Rift was used with two controllers.

Scenarios

The choice and design of appropriate scenarios for ET to treat acrophobia is a central aspect. Bridges, towers, staircases, and rooftops are often mentioned as suitable environments for the exposure of height in-vivo and in-virtuo in the literature [139, 151, 239]. During the conducted interviews, elevators were also mentioned as an appropriate scenario for exposure. Patients with specific phobias suffer on average from three specific phobias simultaneously [142]. Therefore, it is not uncommon for patients with acrophobia to also suffer from claustrophobia. Scenarios should also allow gradual exposure to the anxiety-inducing stimuli (*R1*). For this purpose, bridges and towers in VE are particularly suitable, since their dimensions and characteristics are relatively easy to adapt and to scale in the VE. This also applies to staircases and parking garages. In VE, many parameters can be easily adjusted, e.g. transparency of floor and walls, availability and height of railings or other anxiety causing or reducing elements. Simulating instability of bridges, for example, can also be used as an additional factor of scaling the potential for anxiety generation. Thus, suspension bridges can cause discomfort and feelings of insecurity even in people without acrophobia. These adjustments are similar to the *Difficulty Factors* from Chapter 4 which were used to control the difficulty of the task (**RQ1**). Here, the potential for anxiety generation is controlled with the help of these adjustments. Based on these considerations, a tutorial level and two scenarios were designed (*R1*).

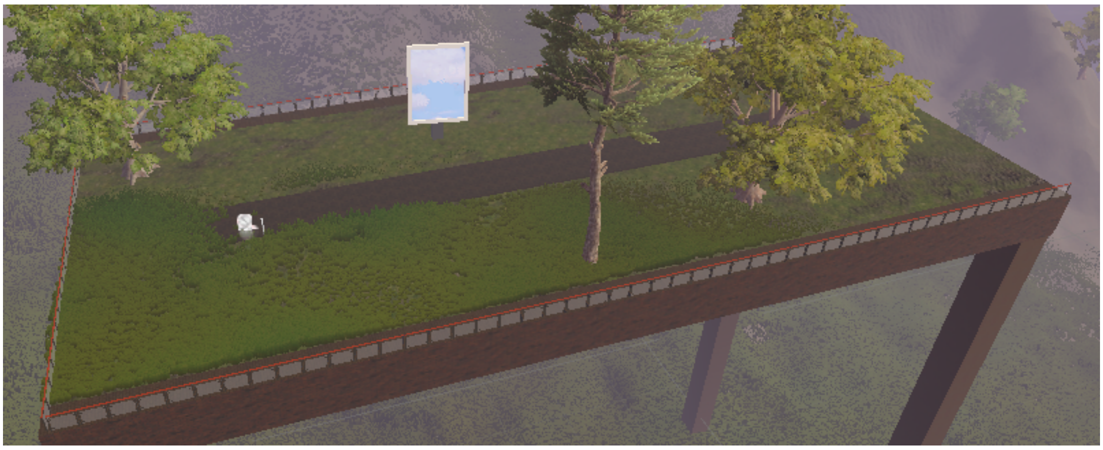


Figure 5.1: VE of the application where the tutorial takes place. Image from Wagner et al. [238] © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

Tutorial Scenario An initial area was designed as the starting point for every ET session. It is intended to create a safe atmosphere, but also to provide a first look into the VE, where the exposition tasks will take place (see **Figure 5.1**). This area is also used for the introduction to the scene and the tutorial for the controls. The platform is enclosed by railings and is large enough to be considered safe.

Bridge Scenario The *Bridge Scenario* consists of a number of platforms that are connected by bridges. With each bridge, the availability of security elements (like railings) decreases, to increase the perceived threat in the user (see **Figure 5.2**). These bridges have different characteristics representing different degrees of difficulty (*R1*):

- availability of railings and the narrowness of the bridge,
- perceived stability of the bridge, for example by using a suspension bridge or placing objects on it that move due to physics,
- using holes in the bridge or transparency to make the depth below more prominent, and
- varying the bridge length together with the distance between platforms.

Using all of these characteristics, six different bridges were created (see **Table 5.1**). The bridges were sorted according to the personal assessment of difficulty. However,

Table 5.1: Characteristics of the six bridges. Table from Wagner et al. [238].

Bridge	Characteristic
1	solid ground, railings
2	solid ground, no railings
3	unstable ground, no railings
4	unstable ground, elements may fall down
5	solid ground, transparent, narrow
6	solid ground, pillars with spacing

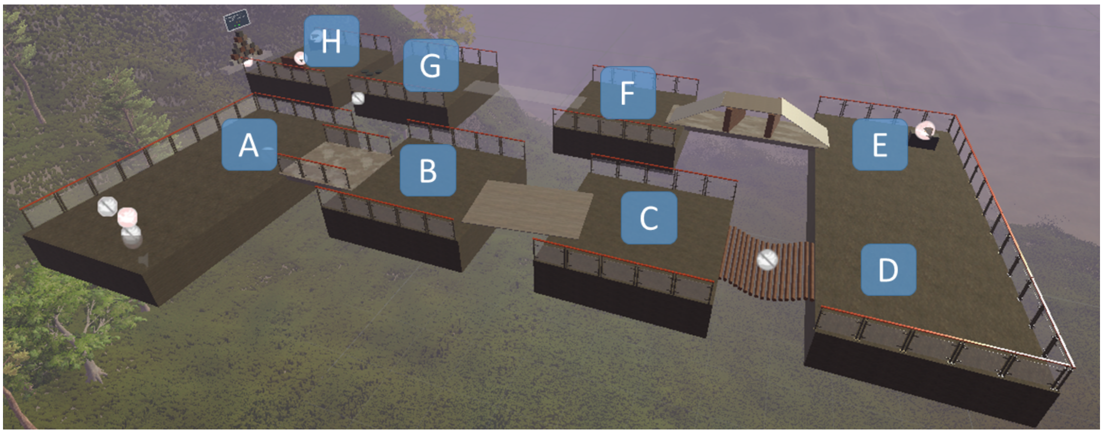


Figure 5.2: *Bridge Scenario* with the locations of the anxiety rating requests (taken from [238]) © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

the uniqueness of each individual case of acrophobia makes it unlikely that varying all these aspects between the bridges will yield a strict order to escalate anxiety for graded exposure. Any given bridge may be rated differently in terms of anxiety levels by different individuals.

Therefore, there will not be a standardized order of the bridges, resulting in an increasing degree of difficulty for all patients. Also, to determine the appropriate order would involve a separate study presenting them to patients suffering from acrophobia. Even if the bridges can be aligned in roughly ascending order, the fact that the difficulty likely will not increase strictly for each individual patient can be considered as an element of *pacing*. Some bridges might represent an especially tough challenge for a certain patient. For example, the fourth bridge is unstable and can collapse during the crossing so that the user has to hurry. But if all the above aspects of the bridges are varied, it is likely that a later bridge will appear easier from their perspective, which may provide

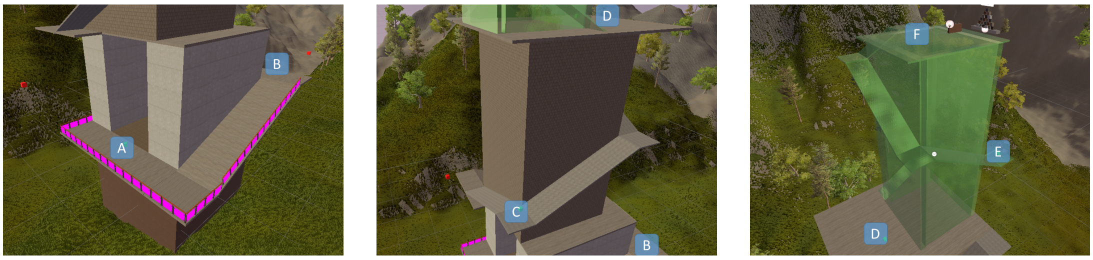


Figure 5.3: *Tower Scenario* with the locations of the anxiety rating requests. Images from Wagner et al. [238] © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

a feeling of accomplishment and a temporary release of tension.

In order to allow the user to concentrate on the next relevant bridge, the next bridge only appears when the previous one has been successfully completed. This is intended to give the user less ambitious goals and thus prevent overwhelming demands and resignation.

Tower Scenario For the *Tower Scenario*, the patient's main task is to ascend a tower to the top. To provide more opportunity for height exposure, the tower is scaled by walking along slopes at its outside wall. Since the *Tower Scenario* is specifically intended to be the most difficult scenario, a tower design with outside ramps was realized (see **Figure 5.3**). Since climbing a tower steadily increases height, it is a good fit for graded exposure. At the beginning the ramps are still very wide and have railings. In the further course the railings disappear and the ramps become narrower. A platform in the middle of the tower can be used to provide rewards and give the patient a break from exposure. The second half of the tower consists of a transparent material, which makes it more difficult to direct the attention away from the environment by staring at a wall or the floor, and narrow ramps without railings should reflect the highest degree of difficulty (*R1*).

Customization of the VE

In order to customize the experience based on the needs of an individual patient, a couple of parameters were implemented, which the therapist can adjust. To increase the degree of immersion and the possible feeling of anxiety, virtual wind is generated depending on the height of the platforms, which moves the trees and is conveyed in the form of sound. An application parameter "wind strength" is intended to influence the perceived difficulty of the environment in terms of anxiety. The therapist is able to adjust the height of the platforms and the wind strength separately or to automatically adjust the wind strength depending on the height of the platform. The wind strength parameter controls the volume of the constantly played wind sound and how much the tree models are animated and distorted like real trees in the wind. Gromer et al. [240] also used wind in their acrophobia VRET environment in a CAVE. They used fans to simulate wind for tactile feedback. However, this had no significant influence on the level of presence. Nevertheless, the integration of wind as a visual and acoustic element into the VE can increase the plausibility of the environment and thus the level of presence.

In addition, the therapist has the possibility to decide whether water should be at the bottom of the environment or not. Water can create a feeling of insecurity, as the depth of the water cannot be estimated.

Before the actual session, the therapist can test the environment and adjust the parameters directly in the VE via an according menu. This enables the therapist to better assess the effects of the parameters on the environment and the patient's later experience. It was assumed that this will be the case especially at the beginning of the use of the VR application. Later, with more experience in the use and effects of the parameters, it is assumed that the remote control panel will be used more often.

Locomotion

As in most VR applications, the locomotion method (*R2*) is a very important aspect that contributes a lot to the user's experience of the VE. In ET, it is particularly important to allow a gradual approach to the anxiety-inducing stimulus so that the patient is not unexpectedly placed in a situation that is very uncomfortable for them. Therapy is much about trust between the therapist and the patient. Thus, the VR application, which serves as a mediating medium for the therapist, must also run reliably so that this trust is not lost. Free *teleportation* is rather unsuitable as a locomotion technique for VRET. However, teleportation could be used if the user should only be able to teleport to predefined locations in VE. In the developed scenarios, however, it is necessary for the user to be able to move freely in the VE, e.g., to experience the step-by-step process of crossing bridges. Unfortunately, since the VE extends over relatively large distances, simply moving around in the tracking space is not sufficient. So alternatives here are only movement by controller (joystick) and walking-in-place (recall Section 2.2.3). In this version of the application the joystick movement was used. Thus, the user is able to use the joystick for locomotion (right controller), looking around and controlling the direction by turning their own body. The disadvantage of this locomotion technique is the high potential for the occurrence of *VR Sickness*. Here, *walking-in-place* could be a suitable alternative. These two methods could be compared in a study.

Anxiety Reporting

Anxiety levels during normal ET are typically reported by stating a number on a predefined scale and the therapist notes the values. In the developed application, the patient can rate their perceived anxiety on a scale from 1 to 9 (from low to high anxiety) by using the joystick of the left controller (see **Figure 5.4**). This allows the anxiety values to be recorded automatically and can then be analyzed afterwards (*R3*). **Figures 5.2** and **5.3** show the positions where anxiety level reporting is requested.

Motivational Elements

In order to slowly confront a patient with their feelings of anxiety, it is also important to include smaller breaks between exposures where the patient is able to relax. Due to the importance of continuous therapy, it is essential to prevent a patient from quitting the therapy. Therefore, this process should be made as pleasant as possible for them. Motivational elements, such as small rewards, can help with this. These motivational elements can be used to ensure that the patient continues the therapy over several sessions and also has the feeling of progress. In this way, motivational elements can also be used to keep the patient constantly aware of the progress they have made so far. If this is directly done in the VE, the patient does not only associate negative emotions with the system and this would also reduce the probability of dropout. In the following, the implemented ideas for collectible badges as rewards and a closing game for a positive ending of a therapy session are discussed (*R4*).

Collectible Badges A frequently used method to increase motivation in video games are collectibles/achievements. These are awarded for special actions/performances and

Figure 5.4: Anxiety reporting function to indicate the current anxiety level. Image from Wagner et al. [238] © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

(a) Treasure chest with badge (b) Pinboard with collected badges

Figure 5.5: (a) chest with a badge inside used as motivational element and (b) pinboard as progression measure. Images (a) and (b) from Wagner et al. [238] © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

thus provide a motivation for the user to do the necessary things. They also serve to show the user what they have already achieved. These aspects can also be used in VRET. Therefore, collectible badges have been integrated into the system, which are presented to the patient at different locations in the scenarios. They serve as extrinsic motivators between exposure sections. For example, they are awarded in the middle and at the end of the *Bridge* and *Tower Scenarios* (silver and gold badge).

To increase the feeling of earning a badge more actively for the patient, the badges are in closed chests. The patient must therefore make a certain effort to obtain the badge. This can lead to an increased perceived value. For this, the user must first open the chest, then grab the badge and attach it to a pinboard (see **Figure 5.5a** and **5.5b**). This pinboard is also used later on so that the user can take another look at the badges they have already earned and become aware of their achievements made so far (*R4*).

Closing Game Not only the feelings and emotions during exposure determine whether a patient continues or discontinues therapy. Kahnemann and Tversky [241] created the notion of the *peak-end rule*. This rule states that two factors are mainly responsible for how one remembers an experience. The most extreme moment (either most painful or most pleasant) plays a role, but so do the last moments of an activity. According to Kahnemann and Tversky, these two factors play a crucial role in whether an activity is repeated. Since the most extreme experience will occur during the exposure itself, the last moments of a session can be taken as a possibility for a pleasant activity.

Thus, a simple game was designed to be fun for the user, after they passed exposition tasks. The rules of the game are simple: the user grabs the stick and moves towards a marking that must not be crossed in order to gain points for shoving the objects (see **Figure 5.6**). There is a small gap between the user's platform and the platform that is holding the stack of boxes. This gap is intended as an additional exposure element. Points are rewarded for every object that falls off the platform. When the platform is empty, the game is completed and the final score is presented in order to add a competitive element.

5.3 Study Outlook

No study has been conducted yet for the presented application. The developed application gives a lot of possibilities and freedom for evaluations. Therefore, potential study objectives will be described and discussed in the following.

Potential for the Generation of Anxiety To be useful as a therapy tool for patients with acrophobia, the VE must be able to induce anxiety in the patient to a suitable degree. This requires a high level of *Sense of Presence* in the patient so that the feeling of anxiety is comparable to situations in the real world. For a study, the anxiety reporting function can be used to request feedback from the user on their current anxiety level at predefined locations. **Figures 5.2** and **5.3** show suggestions for locations where these requests could be placed. In the *Bridge Scenario*, for example, an evaluation of the different bridges is enabled to make a statement about their degree of difficulty. With the help of the configuration options of the therapist, further variants can be created, which can have an influence on the perceived difficulty. Such a study could verify the requirement *R1*.

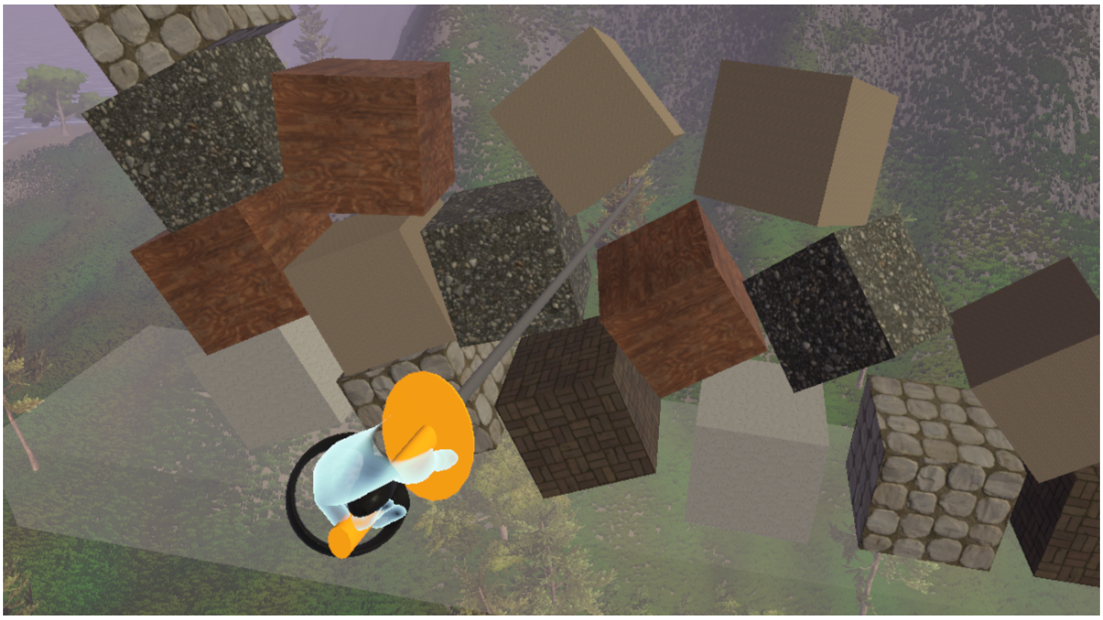


Figure 5.6: Closing game at the end of the *Tower Scenario*. Image from Wagner et al. [238] © 2020 The Author(s) Eurographics Proceedings © 2020 The Eurographics Association.

Locomotion Techniques Furthermore, different locomotion techniques could be compared. Especially walking via joystick and walking-in-place could be suitable. For this purpose, *VR Sickness* has to be investigated. A key factor is that the symptoms of *VR Sickness* and symptoms of anxiety can overlap considerably. That means, here it could be investigated at the same time to find suitable aspects for the separation of the symptom origin. *VR Sickness* symptoms can reduce the *Sense of Presence* [87] and can therefore also influence the perceived anxiety, which could reduce the effectiveness of the therapy.

Motivational Elements Since it is important that the patient attends therapy in the long term, the effects of the motivational elements developed could be studied. Possible research questions could be:

- Do the motivational elements lead to a lower dropout rate compared to patients without these motivational elements?
- Do patients with motivational elements feel more involved in the scene and feel more pleasure when using it?

This could lead to a more pleasant feeling during the therapy for the patient, which in turn could reduce the dropout probability. It would be conceivable that these motivational elements only help to increase the patient's interest in the short term, because they feel new and rewarding, especially at the beginning, but weaken in their effect over time. Developing other motivational elements to increase variety could help slow down this process. Questionnaires such as the Intrinsic Motivation Inventory [242] could be used to evaluate the motivational elements. To evaluate them in terms of appropriateness and patient interest, a few therapy sessions would be sufficient. However, to investigate the effect on the therapy and, for example, the dropout rate, long-term studies in the therapeutic setting would be necessary.

Usage as a Therapy Tool Once the previous questions have been investigated and any necessary adjustments to the application have been made, the system can be used to test whether the tool is suitable for the treatment of acrophobia. Here, the VRET results could be compared with in-vivo ET, as it has already been shown in the work of Emmelkampf et al. [145, 147]. While some aspects of the previous suggestions for potential studies could be investigated with subjects without acrophobia, patients suffering from acrophobia are mandatory for such a study. To determine whether a patient suffers from acrophobia, the *Visual Height Intolerance Severity Scale* questionnaire [243] can be used. The advantage of our system is that the therapist has been given freedom to configure the VE. The very modular developed *Bridge Scenario* can also be easily extended by further bridge variants.

5.4 Summary & Discussion

In this chapter, an application was presented that could be used for the therapy of acrophobia patients. The application consists of a *Tutorial Scenario* and two exposure scenarios (*Bridge* and *Tower Scenario*). The scenarios are designed to consist of customizable elements (platform height, wind strength, water on the ground) that the therapist can configure before starting the therapy to adjust the task difficulty (**RQ1**). In addition, especially the *Bridge Scenario* is very modular and thus can be extended quite easily (additional platforms, additional bridges, variable bridge lengths). To make the therapy more pleasant for the patient, two motivational elements have been integrated into the system. These aim to increase the patient's motivation and thus achieve long-term and regular participation in the patient's therapy sessions. The anxiety levels that would otherwise be queried during a session at ET can thus be automatically queried and subsequently stored with the help of the anxiety reporting system. These can then be evaluated and visualized at the end of each therapy session.

The defined requirements (recall Section 5.1) *R2 - Suitable Locomotion Technique* and *R3 - Anxiety Reporting Function* could be fulfilled. The chosen Locomotion technique allows gradual exposure and cannot suddenly put the patient into unexpected situations. In addition, an easy-to-use reporting system could be integrated to facilitate the therapist's work. Requirements *R1 - Appropriate Scenarios* and *R4 - Increase Motivation/Visualize Therapy Process* need to be evaluated with user studies. Although necessary steps have been taken to fulfill the requirements, only study results can confirm whether the desired effects occur and represent the main limitation of this work.

The availability of railings, walls and a floor is highly important. These can be used to de-escalate situations. However, offering virtual railings that are not actually graspable could lead to problems as well. Moreover, the representation of the user's body can also have a positive effect on the feeling of presence. Juan et al. [151] report that the permanent visibility of the own body in the CAVE was a big advantage with regard to the sense of presence. According to the current state of the technology of full body tracking, however, this would also be possible with VR headsets and, therefore, offers a high potential for improvement.

Another promising approach would be to record physiological data and analyze it over the course of the session. Also an adaptation of the VE based on the current physiological data is interesting. Research on interactive environments adapted to physiological data already exists. For example, Nacke et al. [244] focused on physiological data in video games.

The main focus in the development of the presented application was the use by the patients. However, the involvement of the therapist also plays a central role. Thus, Freeman et al. [153] already presented an acrophobia application in which a virtual therapist/coach was used. Another variation would be to bring the therapist into the virtual environment to go through the VE with the patient. However, this prevents the therapist from observing the patient's real responses. Thus, this feature would probably only make sense in some situations and would not last the entire therapy session. A control panel, on the other hand, as designed for the therapist by Rizzo et al. [186] (recall Section 3.3) for their application to the treatment of PTSD, would also be conceivable for acrophobia. This control panel could give the therapist control over parameters of the VE that the therapist can adjust during the therapy session, it could display the image currently seen by the patient and also physiological data such as the heart rate. Thus, task difficulty could be adjusted automatically (depending on physiological data) or by the therapist during a session (**RQ1**).

6 Conclusion

This chapter summarizes the main contributions of this thesis, i.e. the assessment of USN in stroke patients and the therapy of acrophobia, and gives a general outlook on the use of VR in rehabilitation and therapy.

In addition to the work presented in Chapters 4 and 5, two other papers were published as co-authors during the doctoral period. In the first paper [245], a game was developed using a brain-computer interface to help children with Attention Deficit Hyperactivity Disorder to improve their concentration. The second work [246] dealt with gamification elements in a desktop-based rehabilitation program for cognitive rehabilitation. Here, a specially designed visualization of the therapy progress was compared with and without gamification elements. The findings of this work could be used to visualize the therapy progress for a possible training program based on the application from Chapter 4.

6.1 Summary

6.1.1 Virtual Reality Road Crossing for Unilateral Spatial Neglect Rehabilitation

Two studies were conducted related to the cognitive rehabilitation of stroke patients with VR. The scenarios for these VR applications were virtual road crossings. The first study was conducted with healthy participants to identify *Difficulty Factors* that can be used for an application for patients to scale the task difficulty adequately. This was important, on the one hand, to test its usability first in healthy subjects before testing it with patients whose limitations might interfere with its usability. Furthermore, it was very important for the further development to analyze the influences of the traffic factors on the task difficulty in order to be able to use them appropriately to scale the difficulty.

The knowledge gained from the first study could therefore be directly incorporated into the further development of the application. This application was developed specifically for usage on stroke patients. An essential component was to make the VE as lively as possible and thus ensure a high distraction potential. Stroke patients with USN have particular problems to focus their attention on single tasks. Using this VR application, it was possible to highlight factors that are suitable for distinguishing between stroke patients with and without USN (**RQ2**), i.e. the overall *Decision Time*, *Error Rate* and *Head Direction Ratio* especially considering the *Traffic Direction*.

It was shown that all patients in our study were able to use iVRoad without difficulties and side effects (**RQ3**). However, the interaction and locomotion of the system was deliberately kept very simple to be as compatible as possible for stroke patients. More complex interactions and locomotion techniques can lead to issues that make it difficult to use for stroke patients. Most of the patients also reported that they had a lot of fun using the system. Together with the promising results regarding the separability of the patient groups, the introduced application represents a viable alternative to the conventional assessment tests, whose sensitivity is often insufficient especially in the chronic USN phase [229]. In the future, these factors and their influences have to be analyzed in more detail in order to be able to make an accurate and reliable statement about whether a stroke patient suffers from USN. It would also be interesting to know how many trials are necessary for this. Are the 24 tasks performed in our study sufficient? Or are more or even fewer tasks necessary to be able to make a reliable statement?

An essential aspect in therapy and rehabilitation is an appropriate level of difficulty, which was also the subject of the first research question (**RQ1**) of this thesis. The difficulty level must always be challenging, but not so difficult that it frustrates the patient. At the same time, it should not be too simple; otherwise, the patient might get bored. So the level of difficulty must be precisely adaptable to the particular patient and their situation. This adaption can be done before a therapy session, or the system can automatically adjust it, depending on how the patient performs. In the presented application iVRoad (Chapter 4), the initial focus was on factors defining traffic flow. However, it has been shown that the VE itself also has a large impact on it, such as through the potential for distraction by various stimuli.

There is potential for improvement with regard to the VE. New and also more varied scenarios should be created, especially for the use as a training system. In an assessment, the system needs to be used for only one session. To be successful, the training would need to be used regularly over a longer period of time, as in therapy for acrophobia. This could be used primarily for the general improvement of attention, but also for learning compensation techniques for stroke patients with USN. Furthermore, the transfer to everyday life would be a topic with great potential here. Thus, it could be verified whether a transferability of what has been learned in the VR application is also applicable to real road crossings.

6.1.2 VR Therapy of Acrophobia

The successful applicability of VRET for patients with acrophobia has already been demonstrated [153]. The application presented in this thesis consists of a total of three scenarios, i.e. a *Tutorial Scenario* and two exposure scenarios (*Bridge* and *Tower Scenario*). In the *Tutorial Scenario* the patient can get used to the VE and the control is explained. The two exposure scenarios rely on different exposure elements (bridges and a tower). These provide a gradual increase in the potential for a feeling of acrophobia. The therapist also has the possibility to adjust parameters to adapt the VE individually to the patient and customize the task difficulty (**RQ1**). So far, these can only be adjusted before the therapy session. In the further development, it could be considered to make some elements adjustable during the runtime by the therapist, so that it is possible to actively intervene in a therapy session. In order to relieve the therapist, an anxiety reporting function was implemented, which automatically requests current anxiety values from the patient at predefined locations. Motivational elements were integrated to increase the patient's motivation. Since no study has been conducted for this application yet, an outlook on potential questions for future studies was presented.

The adjustable parameters of the presented system for the treatment of acrophobia (Chapter 5) are suitable to scale the difficulty level and thus the potential induced anxiety in the patient (**RQ1**). In this context, besides the height of the platform, aspects such as the material of the floor and the height of the railings are interesting parameters, which offer more freedom for adjustments compared to the real world. The abstract appearance of VE from Chapter 5 also allows easy extensions by new aspects.

6.2 General Outlook on VR for Rehabilitation and Therapy

In conclusion, a general outlook on the future use of VR in rehabilitation and therapy will be given here. Due to the cost reduction of modern VR headsets, they have become more affordable for a broader audience, but it is still far away from every household having its own VR headset. Smartphones, on the other hand, are now common in most age groups and could be used for simpler VR applications. However, costs are also not only incurred by the hardware. Especially the costs for the development of VR applications can be very high, even if today's game engines simplify the development. For the reproduction of ADL, there are often many aspects to be considered in order to induce a realistic feeling in the patient. Medical staff must also be trained to use VR technology and, in particular, the applications to be used. This is where additional costs arise. However, the use of VR technology can relieve the medical staff in the long term, so it can be a worthwhile investment.

For the two applications presented, it was an essential component to create suitable locomotion and interaction possibilities that can also be used by the respective patient group and are suitable for the intended purpose. Thus, in the VRET application of this thesis, it was only necessary to adapt the interaction to the application purpose, since the patients normally do not have any physical impairments. For the application of VR in stroke patients, it is more complicated. Here, the interaction must be suitable for the application, but at the same time attention must be paid to the potentially existing limitations of the patient group. These can be extremely diverse in stroke patients. In addition, attention should always be paid to side effects such as *VR Sickness*. However, not only the interaction methods can be adapted to the requirements of the patient group, but also the interaction device. For example, conventional VR controllers are designed for healthy users and their handling is more oriented towards modern controllers from gaming consoles. These are designed for a broad audience and pay less attention to accessibility. In addition to barrier-free interaction devices, comfort also plays an important role. Wearing a VR headset for a long time and on a regular basis can still be very exhausting for the user. For patients with head injuries, the use of VR headsets might still be impossible. Special lightweight VR headsets could be developed, which may offer less visual quality, but a higher wearing comfort so that patients, but also users in other areas, are willing to use VR headsets longer and more regularly.

In addition, the aspect of hygiene has become an important issue. The use of the same

VR headset by multiple users can pose an infection risk for diseases. While there are replaceable pads and also special face masks to avoid direct skin contact with potentially infectious surfaces, this presents another barrier to regular VR headset use. In addition, during the current COVID-19 situation, it is usually necessary to wear a medical face mask during studies and rehabilitation measures. This can lead to misting of the VR headset displays and can reduce the visual quality and general wearing comfort.

The great potential of VR in rehabilitation and therapy has been proven many times now. VR should really only be used when conventional therapy methods are insufficient, and not just to take advantage of the currently prevailing VR hype, when there are actually no advantages from using it.

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