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Computer-Based Social Anxiety Regulation in Virtual Reality Exposure Therapy

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COMPUTER-BASED SOCIAL ANXIETY REGULATION IN VIRTUAL REALITY EXPOSURE THERAPY

COMPUTER-BASED SOCIAL ANXIETY REGULATION IN VIRTUAL REALITY EXPOSURE THERAPY

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. Dr. ir. Tim van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 15 juli 2019 om 15:00 uur

door

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Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

Robert Frost (1874–1963). Mountain Interval. 1916.

To my dearest family, the HARTANTOs
—for rising me with a love of science,
and for giving me the faith to believe in myself.

CONTENTS

Summary xi

Samenvatting xv

1 Introduction 1
- 1.1 Motivation . . . 2
- 1.2 Main Research Question and Hypotheses . . . 4
- 1.3 Research Approach . . . 8
- References . . . 10

2 Automatic Mechanisms for Measuring Subjective Unit of Discomfort 19
- 2.1 Introduction . . . 20
- 2.2 Method . . . 20
- 2.3 Results . . . 21
- 2.4 Discussion and Conclusion . . . 23
- References . . . 23

3 Controlling Social Stress in Virtual Reality Environments 25
- 3.1 Introduction . . . 26
- 3.2 Related Work . . . 27
- 3.3 Method (First study: Social Scene Experiment) . . . 28
  - 3.3.1 Ethics Statement . . . 28
  - 3.3.2 Experiment Design . . . 29
  - 3.3.3 Participants . . . 29
  - 3.3.4 Measurements . . . 29
  - 3.3.5 Procedure and Apparatus . . . 30
  - 3.3.6 Result . . . 31
  - 3.3.7 Discussion . . . 32
- 3.4 Method (Second study: Dialogue Stressor Experiment) . . . 33
  - 3.4.1 Ethics Statement . . . 33
  - 3.4.2 Dialogue Stressor . . . 33
  - 3.4.3 Experiment Design . . . 34
  - 3.4.4 Participants . . . 35
  - 3.4.5 Measurement . . . 36
  - 3.4.6 Procedure and Apparatus . . . 37
  - 3.4.7 Results . . . 37
- 3.5 Discussion and Conclusion . . . 45
- References . . . 47

4 Computer-based Fear Regulation during Virtual Reality Exposure for Social Anxiety **53**
4.1 Introduction . . . 55
4.2 Related Work . . . 56
4.3 System Design . . . 58
4.4 Hypotheses . . . 63
4.5 Method . . . 63
4.5.1 Ethics Statement . . . 63
4.5.2 Experiment Design . . . 63
4.5.3 Participant . . . 64
4.5.4 Measurements . . . 64
4.5.5 Procedure and Apparatus . . . 66
4.6 Data Preparation and Analyses . . . 67
4.7 Results . . . 68
4.7.1 Automatic Anxiety Calibration Session . . . 68
4.7.2 Analysis Outcome Measures . . . 68
4.7.3 Analysis Process Measures . . . 72
4.8 Conclusion and Discussion . . . 75
4.8.1 Main Finding . . . 75
4.8.2 Limitation and Future Work . . . 76
References . . . 77

5 Home-Based Virtual Reality Exposure Therapy System with Virtual Health Agent Support **83**
5.1 Introduction . . . 84
5.2 Related Work . . . 84
5.3 System Design . . . 85
5.3.1 The Virtual Health Agent . . . 85
5.3.2 The Virtual Reality System . . . 88
5.4 Evaluation . . . 91
5.4.1 Subjects . . . 92
5.4.2 Procedure and Apparatus . . . 92
5.4.3 Measures . . . 92
5.4.4 Results . . . 92
5.5 Conclusion and Discussion . . . 94
References . . . 94

6 Discussion and Conclusions **97**
6.1 Limitations . . . 101
6.2 Contributions . . . 101
6.2.1 Scientific Contributions . . . 101
6.2.2 Practical Contributions . . . 103
6.3 Future Research . . . 104
6.4 Final Remarks . . . 105
References . . . 106

Acknowledgements **111**

Appendix A **113**

Appendix B **115**

Appendix C **117**

Appendix D **119**

Curriculum Vitæ **121**

List of Publications **123**

SUMMARY

SOCIAL anxiety disorder (SAD), commonly referred to social phobia, is one of the most often occurring types of mental disorders. Individuals with social phobia encounter an immense and unreasonable fear of social interaction. Cognitive behaviour therapy (CBT) is the most thoroughly studied nonpharmacologic approach to the treatment of SAD patients. In CBT, patients are gradually, in vivo, exposed to anxiety-provoking real-life situations until habituation occurs and patients' fear dissipates. Although effective for most patients, there are some clear limitations: some specific and required social situations are difficult to arrange due to unpredictability and possibly short duration of these naturally occurring social interactions, the therapist has limited control over anxiety provoking elements during the exposure, and individuals with social phobia have high refusal rate for in vivo exposure to the dreaded and fearful social situation.

Virtual Reality Exposure Therapy (VRET) has been suggested as an alternative to overcome many shortcomings of in vivo exposure. Contrary to exposure in vivo, in a VRET system the therapist can manipulate the exposure elements in a safer, manageable and cost effective way. A VRET system presents fear eliciting stimuli to the patient in a Virtual Reality environment where the parameters of its anxiety evoking stimuli can be easily gradually manipulated by a therapist. The state of the art and recent enhancement of Internet and VR technology seems to be able to meet the ever-increasing demand for more accessibility and efficiency of mental healthcare services by bringing the VRET system directly at patient's home. This thesis presents the development and evaluation of such an envisioned home-based VRET system for SAD patients.

The blue print of the envisioned system design entails several key elements that need to be established. All those key elements were investigated and evaluated empirically in three separated studies followed up by a feasibility study. The first key element identified, is the system's ability to measure the patient's anxiety level automatically. Traditionally in VRET this is done using self-reported anxiety measurements, where patients are asked to report their anxiety every four or five minutes. Without the direct involvement of a therapist, it is up to the system to determine the appropriate timing, therefore, the timing is a crucial element. An empirical study involving 24 participants investigated the effects of three different types of automatic self-reported anxiety timing mechanisms (dialogue dependent, speech dependent and context independent). The results showed that the participants preferred a dialogue dependent timing mechanism above speech dependent or timing dependent mechanism, since it was considered as less interruptive. Moreover, the study also confirmed the needs for an accurate automatic self-reported anxiety timing mechanisms, as it could affect people's experience and their behaviour in a dialogue with virtual human.

The second key element is the system's ability to elicit and control the anxiety evoking stimuli within the social scene. This was investigated in two successive empirical studies. The first study investigated whether an exposure to various virtual social sce-

narios was associated with different levels of anxiety. The 24 participants were exposed to a free-speech dialogue interaction with a virtual character in a neutral world, blind date and job interview setting. The results showed that the participants' level of anxiety increased significantly from the neutral world, the blind date to the job interview. This indicates that various virtual social scenarios are indeed able to evoke different levels of anxiety. The second study investigated anxiety control within a dialogue in VRET system. For this, the study assessed the association between the ratio of negative and positive dialogue responses made by a virtual character and individual's level of anxiety. Twenty-four participants were exposed to two different experimental conditions: a positive, and a negative virtual job interview condition. In the positive condition, in the course of time the number of positive responses from the virtual character increased while negative responses decreased. In the negative condition, the opposite happened. The results showed that the manipulation of the dialogue style in both conditions had a significant effect on people's level of anxiety, their attitude, their speech behaviour, their dialogue experiences, their own emotion, and how they perceived the emotion of the virtual human. These finding demonstrate that social dialogues in a virtual environment can be manipulated for therapeutic purposes effectively.

The third key element of the envisioned system is the possibility to introduce autonomous anxiety regulation. Traditionally, in the clinic a therapist tries to regulate the patients' anxiety. However, in a home situation, a system would have to do this regulation automatically. A third empirical study was conducted to investigate and evaluate the ability and effectiveness of an automatic feedback-loop regulation mechanism for maintaining individual's anxiety on a predefined target level. A group of 24 participants were exposed into two different system response conditions: a static and a dynamic condition. In the static condition participants were exposed to a static set of virtual reality stressors while in the dynamic condition they were exposed to a set of virtual reality stressors that changed dynamically aiming at keeping the anxiety of the participants at stable level. In the static condition, the anxiety dropped as indicated by decreased self-reported anxiety, decreased heart rate, increased heart rate variability, and longer answers. In contrary, in the dynamic condition, the participant's anxiety level was maintained around a pre-set anxiety reference level. Therefore, the findings demonstrate that individuals' level of anxiety can be regulated automatically using an automatic feedback-loop mechanism.

Besides those three important key elements of the system design blue-print, the envisioned system also has a number of practical and important elements such as the development of a virtual health agent, the therapist application, and a secure remote database server. Together these elements lay the foundation for a home-based VRET system. To evaluate the feasibility of such proposed system to treat people with SAD at home, an empirical study was conducted. The home-based VRET system was evaluated with a group of five social anxiety disorder patients. All patients received a complete home-based VRET system and were scheduled to perform 10 treatment sessions at home. The study findings showed that the proposed system could evoke the required anxiety, as expected, which over time dropped as patients' self-reported anxiety and heart rate gradually decreased during the exposure sessions.

To conclude, this thesis argues that the proposed home-based VRET system could

evoke the required anxiety in patients with substantial level of presence. By meeting the above mentioned key challenges of our study, we showed that an effective home-based VRET system can be built and provided in due course. Therefore, this finding suggests that delivering a home-based VRET system is indeed possible, which could provide numerous benefits for both patients and therapists.

SAMENVATTING

SOCIALE fobie is een van de meest voorkomende geestelijke stoornissen. Personen met sociale fobie hebben een enorme en onredelijke angst voor sociale interacties. Cognitieve gedragstherapie (CBT) is de meest bestudeerde non-farmaceutische behandeling voor sociale fobie. In CBT worden patiënten geleidelijk blootgesteld aan echte (in vivo) angst oproepende situaties die in het dagelijks leven voorkomen, totdat gewenning plaats vindt en angst afneemt. Hoewel dit effectief is voor de meeste patiënten zijn er een aantal duidelijke beperkingen: sommige specifieke sociale situaties zijn moeilijk voor op te zetten omdat ze onvoorspelbaar en kort zijn; de therapeut heeft maar beperkt controle over de elementen die angst oproepen tijdens de blootstelling; en personen met sociale fobie weigeren vaak deze beangstigende sociale situaties aan te gaan.

Virtual Reality Exposure Therapy (VRET) is een mogelijk alternatief dat een aantal van de beperkingen van blootstelling in het echte leven kan overkomen. In tegenstelling tot in vivo blootstelling, kan binnen een VRET systeem de therapeut de elementen die angst oproepen manipuleren op een veilige en kosten effectieve manier. Een VRET systeem presenteert angst oproepende stimuli aan de patiënt binnen een Virtual Reality omgeving, waar de parameters van de angst oproepende stimuli gemanipuleerd kunnen worden door een therapeut. Dankzij state of the art technologie en recente verbeteringen in internet en VR therapie is het mogelijk om aan de vraag naar toegankelijke en efficiënte geestelijke gezondheidszorg tegemoet te komen door een VRET systeem direct naar het huis van patiënten te brengen. In deze dissertatie wordt de ontwikkeling en evaluatie van zo een voorgesteld thuistherapiesysteem virtual reality exposure voor sociale fobie patiënten gepresenteerd.

De blauwprint voor het systeem bevat verschillende elementen die vastgesteld moeten worden. Al deze elementen zijn onderzocht en empirisch geëvalueerd in drie verschillende studies, gevolgd door een haalbaarheidsstudie. Het eerste element is dat het systeem in staat moet zijn het angstniveau van de patiënt automatisch te meten. Traditioneel wordt dit binnen VRET gedaan door subjectieve angst maten te gebruiken, waar patiënten gevraagd wordt elke vier of vijf minuten hun angstniveau door te geven. Zonder de directe aanwezigheid van een therapeut wordt het de taak van het systeem de gepaste timing te bepalen, wat cruciaal is. Een empirische studie met 24 proefpersonen onderzocht het effect van drie types automatische subjectieve-angstmeting timing mechanismen (dialoog afhankelijk, spraak afhankelijk en context onafhankelijk). De resultaten lieten zien dat de proefpersonen een dialoog afhankelijk timing mechanisme de voorkeur gaven boven een spraak afhankelijk of een context onafhankelijk mechanisme, aangezien deze als minder verstorend werd ervaren. De studie laat bovendien ook zien dat een nauwkeurig timing mechanisme nodig is voor subjectieve angstmetingen, aangezien het de ervaring en het gedrag van mensen in een dialoog met een virtueel persoon kon beïnvloeden.

Het tweede element is de mogelijkheid van het systeem om angst-stimulerende sti-

muli op te roepen en te controleren binnen de sociale scene. Dit is onderzocht in twee opeenvolgende empirische studies. De eerste studie onderzocht of blootstelling aan verschillende sociale scenarios geassocieerd was met verschillende angstniveaus. De 24 proefpersonen werden blootgesteld aan een vrije-spraak dialoog met een virtueel karakter in een neutrale wereld, een blind date en een sollicitatie gesprek. De resultaten laten zien dat het angstniveau van de proefpersonen significant steeg in de blind date ten opzichte van de neutrale wereld, en in het sollicitatiegesprek ten opzichte van de blind date. Dit laat zien dat verschillende sociale, virtuele situaties inderdaad in staat zijn verschillende angstniveaus op te roepen. De tweede studie onderzocht angstcontrole binnen een dialoog. Hiervoor werd de associatie beoordeeld tussen de ratio van negatieve en positieve reacties door een virtueel karakter en het angstniveau van een individu. 24 proefpersonen werden blootgesteld aan twee verschillende experimentele condities, een positief en een negatief virtueel sollicitatie gesprek. In de positieve conditie steeg het aantal positieve reacties van het virtuele karakter over de tijd terwijl het aantal negatieve reacties daalde. In de negatieve conditie gebeurde het tegenovergestelde. De resultaten laten zien dat de manipulatie van de dialoogstijl in beide condities een significant effect had op angstniveau, attitude, verbaal gedrag, dialoogervaringen, eigen emotie en hoe de emotie van het virtuele karakter ervaren werd. Deze resultaten laten zien dat sociale dialogen in een virtuele omgeving effectief gemanipuleerd kunnen worden voor therapeutische doeleinden.

Het derde element van het systeem is de mogelijkheid om automatische angstregulatie uit te voeren. Traditioneel gezien probeert de therapeut in de kliniek het angstniveau van de patiënt te reguleren. Echter, in een thuissituatie zou het systeem dit automatisch moeten doen. Een derde empirische studie is uitgevoerd om te onderzoeken en te evalueren of een automatisch feedback-loop regulatie mechanisme effectief was in het stabiel houden van het angstniveau van een individu. Een groep van 24 proefpersonen werd blootgesteld aan twee verschillende systeem condities, een statische en een dynamische conditie. In de statische conditie werden proefpersonen blootgesteld aan een statische set van virtuele stressors, terwijl in de dynamische conditie de stressors dynamisch veranderden en gericht waren op het stabiel houden van het angstniveau. In de statische conditie ging het angstniveau naar beneden wat zich uitte door een afnemende zelf gerapporteerde angst, een afnemende hartslag, een oplopende hartslag variatie, en langere antwoorden. In de dynamische conditie daarentegen, werd het angstniveau behouden rond het vooropgesteld referentiepunt. De resultaten laten dus zien dat het angstniveau van een individu gereguleerd kan worden door een systeem met behulp van een automatisch feedback-loop mechanisme.

Afgezien van deze drie belangrijke elementen van het systeem heeft het ook een aantal praktische en belangrijke elementen zoals de ontwikkeling van een virtuele gezondheidsagent, een therapeuten applicatie en een beveiligde data server. Samen leggen deze onderdelen de fundering voor een thuistherapiesysteem voor VRET. Om te onderzoeken hoe haalbaar het is om met dit systeem mensen met sociale fobie thuis te behandelen is een empirische studie gedaan. Het thuistherapiesysteem VRET is geëvalueerd met een groep van vijf patiënten met sociale fobie. Alle patiënten kregen het volledige systeem mee naar huis en zijn ingedeeld om 10 therapie sessies thuis te volgen. De resultaten laten zien dat het systeem zoals verwacht de benodigde angst kon oproepen. Gedurende

de tijd nam deze angst af, patiënten rapporteerden minder angst, en de hartslag nam af.

Samenvattend, deze dissertatie beargumenteert dat het voorgestelde thuistherapiesysteem voor virtual reality exposure de benodigde angst kan oproepen in patiënten waarbij ze een substantieel aanwezigheidsniveau ervaren. Door tegemoet te komen aan de bovengenoemde uitdagingen laten we zien dat een thuistherapiesysteem voor virtual reality exposure haalbaar is en gebouwd kan worden, wat vele voordelen kan hebben voor zowel patiënten als therapeuten.

1

INTRODUCTION

"Virtual reality was once the dream of science fiction. But the internet was also once a dream, and so were computers and smartphones. The future is coming."

Mark Zuckerberg, Facebook CEO

1

1.1. MOTIVATION

SOCIAL anxiety disorder, commonly referred to as social phobia, is an anxiety disorder with which individuals encounter an immense and unreasonable fear of social interaction. Their fear may intensify due to their lack of social skills or experience in social situations. Commonly, individuals with social phobia have a strong fear of doing something in front of others that will be perceived as humiliating or embarrassing [1], for example, talking in public, doing a job interview, or going on a blind date. People with this disorder usually suffer from distorted cognitions, including holding excessively false self-beliefs about social interactions as well as negative opinions towards others. Although they are capable of recognizing their excessive and unreasonable fear and feelings, they feel powerless to cope with and control their anxiety. Furthermore, these individuals tend to avoid social situations, and are reported to have a high chance of suffering from secondary depression, substance abuse (e.g. alcoholism, drug abuse), restricted socialization (e.g. professional [2,3], romantic [4,3], friendship and everyday informal social interaction [3]), health problems [3], poor employment and education performance [3,5], as well as a decrease in their quality of life [5].

Social phobia is one of the most frequently occurring types of mental disorders. It is the second most common mental disorder in the US population with a lifetime prevalence of 13.3%, with only 35.2% of these individuals seeking treatment [6]. In Europe, reports are slightly lower than in the US. It affects 6.7% of the European population at some point in their lives, with a 12-months prevalence of 2-3% [7]. For the Dutch population, a lifetime prevalence of 7.8% has been reported and a 12-months prevalence of 4.8% [8]. With these recurring numbers, especially in the western world, social phobia produces a large number of intensive usage of (mental) health care services. For example, in 2011 the Netherlands spent 625.5 million Euro on the treatment of anxiety disorders in general [9], and more than 12 thousand people were treated for a social anxiety disorder [10].

A common treatment for patients with social phobia is cognitive behavior therapy (CBT). CBT aims to modify patients' maladaptive cognitions and behavior using both cognitive restructuring and behavioral exposure strategies [11,12]. During exposure in vivo, patients are gradually exposed to more anxiety-provoking real-life situations until their fear dissipates. In vivo exposure exercises are done during therapy or are given as homework assignments, entailing both performance and social interaction situations.

Although in vivo exposure is an effective method, there are some clear limitations. For example, some specific social situations (e.g. performing public speaking in front of a large audience, meeting a stranger at a party, ordering food in a restaurant) are difficult to arrange due to the unpredictability and possibly short duration of naturally occurring social interactions, as well as the need for human resources. All these factors make treatment expensive. Furthermore, therapists have limited control over the exposure elements, such as the audience's behavior in public speaking situations, the reaction of a stranger, or the politeness of a waiter. This makes the planning and the execution of exposure exercises difficult. Also, the refusal rate of exposure to the dreaded and fearful real-life situations is around 20-23% for social phobic patients [13-15], which is considerably high. This also coincides with a large number of patients that drop out during exposure therapy [16]. Finally, the lack of trained therapists results in long waiting lists

for the treatment, and, in rural areas, access to face-to-face therapy is difficult [17].

Virtual Reality Exposure Therapy (VRET) has been suggested [18-22] as an alternative to overcome many shortcomings of in vivo exposure. Several meta-analyses [20,21,19] on VRET for anxiety disorders show comparable efficacy with exposure in vivo. Four recent randomized controlled trials [23-25,16] found VRET to be effective in the treatment of social anxiety complaints. Furthermore, VRET also provides a treatment that is more readily accepted by patients [22]. A study conducted by Garcia-Palacios et al. [22] shows that in a survey among 150 patients, 76% patients chose exposure in virtual reality over exposure in vivo. Additionally, the refusal rate for VRET (3%) was lower than the refusal rate for in vivo exposure (27%) [22].

The approach used in VRET follows basic behavior therapy treatment strategies by producing a virtual environment that resembles feared, real-life situations. However, contrary to in vivo exposure, VRET makes the control of exposure elements safer, manageable and cost effective [26-28]. During the exposure, patients are confronted with computer-generated fear eliciting stimuli in the form of a virtual environment where the parameters of its anxiety evoking stimuli can be easily changed and manipulated gradually by a therapist.

The first experiments [29] in this area were conducted more than two decades ago. Initially, research focused on mental disorders such as claustrophobia, acrophobia, fear of flying, arachnophobia, posttraumatic stress disorder and panic disorder [30]. For specific mental disorders, for example social phobia, most experimental studies on the VRET system often focused on the fear of speaking in public [25,31]. However, other formal and informal social scenarios have also been successfully developed and studied, including a restaurant [32], a train and bus station [33,32], a clothing store [32], a bar [33], a formal job interview [34,35] and a blind date scenario [32]. In these VRET system setups, patients are asked to talk or give a presentation to virtual humans. The virtual humans could be (3D) graphical characters, photo realistic characters or video recordings of real actors [31]. Therefore, the characters' behaviour is often limited in terms of their gestures such as changing their posture, the direction of their eye gaze, their facial expression (e.g. interested, neutral and bored), and uttering a few pre-recorded dialogue sentences - for example making some comments toward the patients, asking them for directions or more explanation. All these characters' behaviors are usually triggered by the therapist using a Wizard-of-Oz method, and are not directly triggered by the patients' behaviour. Even though it is considered as a relatively simple method, it is successful in eliciting anxiety during the exposure [36,37].

With an ever-increasing demand for more accessibility and efficiency of mental health services, and the trend towards more accessible hardware and software to support virtual reality exposure, the idea of the home-based virtual reality exposure therapy becomes an interesting option. This approach moves away from the traditional clinic-centered treatment and moves towards self-therapy that can be done by patients at home at their preferred time. This approach will not only help with reducing the use of intensive mental healthcare services, but also lowers the barrier for seeking professional help [5]. The work presented in this thesis therefore focuses on a home-based VRET system for the treatment of social phobia. It proposes solutions for the technological challenges in this context and evaluates them empirically.

1

1.2. MAIN RESEARCH QUESTION AND HYPOTHESES

THE main research questions addressed in this thesis can be formulated as follow:

How to provide virtual reality exposure therapy for social phobia patients at home?

Figure 1.1 presents the blueprint of the system envisioned in this thesis. It identifies key elements of the system that need to be established. First of all, to evoke the appropriate level of anxiety, it is essential that the system can *measure the patients' anxiety* (cf. Multi-Modal Anxiety Measurement in Figure 1.1). Traditionally in VRET this is done using self-reported anxiety measurement [38], where patients are asked to report their anxiety every four or five minutes. When exposure involves a dialogue with a virtual human, a therapist could normally time an appropriate moment to pose this question without too much interference of the exposure itself. Without the direct involvement of a therapist, it is up to the system to determine the appropriate timing. The position taken in this thesis is that the timing mechanism affects people's experience of the dialogue with a virtual human. Inappropriately timed interruptions have been shown to adversely affect task performance [39,40], but also people's emotional state [41]. In the context of virtual reality, an interruption could mean a break in the feeling of being in the virtual world, i.e. presence, whereby individuals stop responding to the virtual environment, and instead respond to the real environment [42,43]. This feeling of presence in a virtual world is important, as it has been associated with self-reported anxiety [44]. For example, Pallavicini et al. [45] demonstrated that interruptions, in the form of technological breakdowns, can reduce the ability to evoke anxiety by virtual reality.

A second important element of the envisioned system is its ability to elicit and control the anxiety evoking stimuli (cf. Anxiety Level Controller in Figure 1.1). When it comes to VRET for social anxiety, stimuli control is often implemented by moving between social scenes. The position taken in this thesis is that it is also possible to control anxiety-evoking stimuli, i.e. a phobic stressor, within the social scene, specifically by controlling the style (i.e. tone, contents) of the dialogue. Based on the research on other types of anxiety disorder [46], introducing anxiety provoking stimuli within the (social) scene might be beneficial for the treatment of social phobia as well. Take for example VRET for fear of flying: During the session therapists are able to induce and manipulate a specific and relevant anxiety provoking stimuli such as switching on the "fasten your seatbelt" indicator, flying in the different weather conditions or specific pilot announcement in the VR world [47]. Furthermore, in VRET for fear of heights, therapists have the ability to elicit different levels of anxiety within the session by moving patients to a higher step of a staircase or placing them near the edge of a balcony [48]. With regard to social anxiety disorder, this ability has been given little attention. For exposure in the VRET system, specific elements of social anxiety provoking stimuli can be induced, i.e. by manipulating the body posture of a virtual audience [49], the eye gaze of the virtual character [32,50], the distance between the patient and the virtual character [51,52], as well as the facial expression [51,53], attitude [49,54] or the personality [32,55] of the virtual character. However, less research attention has been given to manipulating the verbal element of the interaction, for example the content of the dialogue. Most available VRET systems that establish a social interaction are provided with no or only limited verbal responses

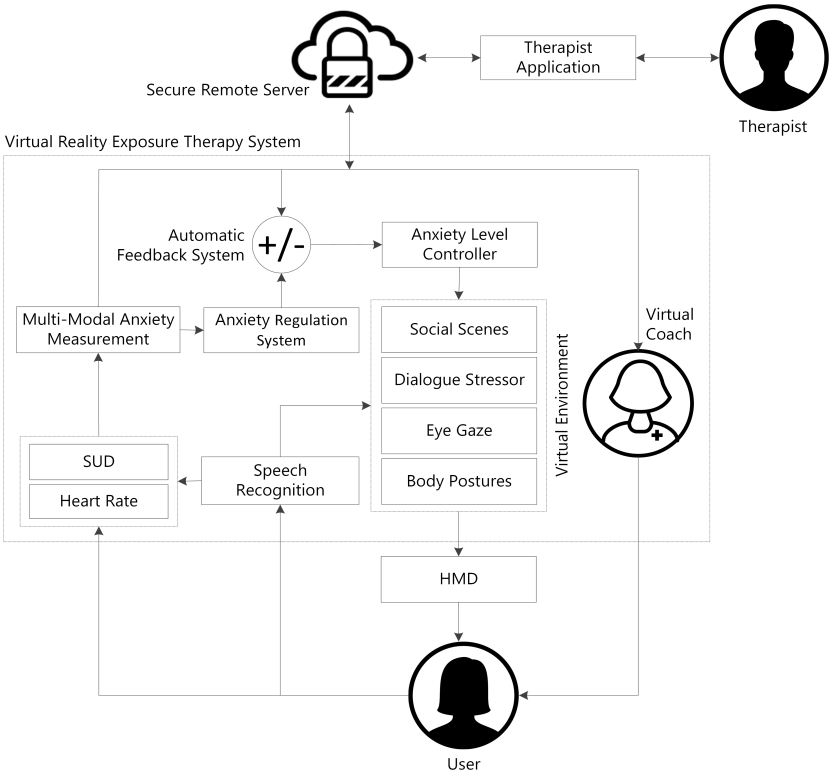

Figure 1.1: Design of the home-based virtual reality exposure therapy system

from the virtual characters. Still there is clear support [56,57,53,58] for the claim that virtual characters that act as social actor during a conversation can elicit a human response similar to one elicited by a human conversation partner. Furthermore, this type of human-character interaction has been found to affect anxiety levels and influence the emotional state of the human [56,57]. This not only has been studied and demonstrated for applications targeting social anxiety [32,49,51], but also for schizophrenia [52]. Affective feedback plays an important role in dialogues between humans since it can elicit defensive or supportive listeners' feedback responses [59]. Take for example an educational setting: Receiving positive instead of negative feedback responses from a virtual character was found to speed up the students' learning time [60,61] and enhance their interest in a topic as well as their self-efficacy [62,63]. Furthermore, extensive dialogues provide multiple opportunities to give patients positive or negative feedback. Therefore, these dialogues could be ideal phobic stressors for a VRET system that can be manipulated during an exposure session.

The third element presented in the blueprint of the envisioned system is the possibility of autonomous anxiety regulation (cf., Anxiety Regulation System in Figure 1.1). Whereas in the clinic a therapist would try to regulate the patients' anxiety, in a home situation, a system would have to do it automatically. The position argued for in this

thesis is that the latter is indeed possible. Using computers to modify people's emotions is not new. Often however this is conducted by using a positive feedback loop whereby the system pushes the emotional state of the patients into a specific direction without a specific anxiety target level. Emotion regulation is internal in this case. It is up to the individual to regulate or modify their emotion. Providing people with biofeedback helps them to alter their emotion in a certain direction. This principle has been used in affective gaming such as Konami dating game [64], Tetris 64 [65], Mindlink [66] and Nevermind [67]. In these games, the system provides players with feedback about their emotion and challenges them to alter it towards a specific goal state. These games use a wide variety of biosensors such as a heart rate monitor, pulse oximeter, and skin conductance apparatus to measure the player's emotional state and provide feedback accordingly. Computer-based emotion modification utilizes biofeedback not only for entertainment, but also for training purposes. For example, Bouchard et al [68] used an adapted first-person shooter game to successfully train a group of soldiers to lower their stress response when confronted with stressful scenarios.

Positive feedback systems that use biofeedback have also been studied for patients with mental disorders such as schizophrenia, depression, anxiety disorder, insomnia, alcohol and drug dependence, and tardive dyskinesia [69,70]. However, in this thesis, the argument is made for using, a negative feedback loop mechanism to regulate patient anxiety levels during a VRET session. In essence, it is the opposite of the positive feedback-loop as it aims to maintain patient's emotion at a certain target level. To move from a positive towards a negative feedback loop system, the challenge is to establish an anxiety scale, where the therapist is able to set a pre-defined target anxiety level. This scale should be aligned with automatically collected emotion measurements from a patient, such as heart rate and self-reported anxiety. Quantifying emotions from measuring data is difficult however [71]. Several studies [72-74] reported the difficulty of classifying emotion automatically because of several issues, for example the lack of a "ground truth" to calibrate or train a system [72] and individual differences in the response towards standardized emotional stimuli used for validating measures [74,73]. Despite these problems, combining several emotion measures has been shown to improve the overall accuracy and reliability of automated emotion measurements [75-79]. This therefore put forward the need for multi-modal anxiety measurement. Furthermore, a scalable stressor is required, which allows for gradual exposure, and avoid situations where patients are exposed to stimuli material that would result in an extreme level of anxiety, i.e. flood [80]. Fortunately, several studies [34,51,52] have already shown that scalable stressors are indeed possible for VRET for social phobia.

The blueprint of envisioned system also has a number of other elements that have not yet been discussed, such as the virtual social scenes, the virtual coach ("virtual health agent"), the therapist application, and a secure remote server, all elements of practical importance. For example, a virtual coach is a virtual character that aims to guide individuals through a specific task, reminding them to engage into an activity, stimulating positive behavior, increasing motivation, or assisting in learning a specific subject or skill [81,82]. It can stimulate adherence of self-management, motivate individuals, and lower treatment costs [83,84]. Virtual coaching has been suggested to support education [85], physical training [83], mindfulness meditation training [86], neuro-rehabilitation [87],

and addressing post-traumatic stress disorder problems [88,89].

Another key element of the envisioned system is the therapist user interface. It is a standalone application used by a therapist to interact and support communication with the patients, for example, registering patients into the system, creating a personalized treatment plan, analyzing patient data, exchanging messages and monitoring the treatment progress. When it comes to VRET technology, most studies only focused on the patient's side, ignoring the therapist side. However, when delivering the treatment remotely [17,32], the therapist's confidence with controlling the system seems essential for the acceptance of the system. Some studies [90-92] have also focused on the usability of the therapist user interface and have proposed various design improvements. Therefore, this thesis work also focuses on developing and establishing a therapist user interface that fits with the treatment protocol therapists are already familiar with.

To provide social phobia patients with a diverse set of anxiety provoking stimuli several virtual social scenarios are needed. Often social situations recommend for exposure in vivo [93] have been replicated in virtual reality [34,23,54]. Besides the physical and social environment, other elements that make up the social scenario should be considered as they can also act as stressors to elicit anxiety, such as the avatar's dialogue style [34], body posture [94], eye gaze behavior [95], attitude [49] and narrative text [96].

The development of secured and centralized database server is another practical and important key element in the blueprint of the envisioned system. The database server serves as a main hub to connect and support the communication between the therapist and patients' application, which includes the virtual coach. The database server records all occurring events during the treatment session, including patients' psychological measurement data, questionnaire results, and therapist-patient messaging activities. To ensure the security, all data stored on the server and the data exchanged between a therapist's application and a patient's application require encryption and compliance with the ISO standard on the medical informatics security guideline (ISO27001, ISO9001, ISO14001 and NEN7510).

Insight into the design, the interplay of all its elements, and how patients would use a home-based VRET system would therefore help in understanding its feasibility. Given the argumentation and the main tenets presented, it is now possible to summarize the main hypotheses tested in this thesis:

> **H1:** *The timing mechanism for obtaining self-reported anxiety experienced during exposure in virtual reality affects an individual's experience of a dialogue with a virtual human.*
>
> **H2:** *The scenario characteristics and the ratio of positive and negative responses from a virtual human in a dialogue with individuals correlate proportionally with the individual's anxiety.*
>
> **H3:** *An individual's social anxiety in virtual reality can be regulated automatically.*

Together these hypotheses lay the foundation of the envisioned home-based VRET system for anxiety disorder treatment. This thesis also takes the next step and puts forward the design of such a system. Its implementation leads to the following research question that is also addressed in this thesis:

1

What is a feasible home-based virtual reality exposure therapy system for social anxiety disorder?

1.3. RESEARCH APPROACH

THE ***first hypothesis*** was tested in an experiment with a group of 24 non-patients. They were asked to give three presentations, each with a question and answer round, in front of a virtual audience. Each session used a different timing mechanism to ask participants to rate their anxiety. These timing mechanisms were: (1) dialogue dependent (i.e. naturally in the flow of the dialogue, e.g. just before the start of a new question by virtual human), (2) speech dependent (i.e. when both user and virtual human were silent), (3) context independent (i.e. randomly). The experiment had a within-subject design, and in each condition data was collect on the participants' feeling of presence, their dialogue experience with virtual humans, and their experience of reporting their anxiety. Furthermore, participant's dialogues with the virtual human after having given an anxiety rating were also recorded and analyzed. This study and its results are presented in *chapter 2* of this thesis.

The ***second hypothesis*** was tested in two successive studies. In the first study, three different virtual social scenarios (neutral world, blind date, and job interview) were tested in an experiment with 16 (non-patients) participants. All participants were exposed to a free-speech dialogue interaction with virtual characters in a blind date and a job interview setting while being monitored by a researcher who played the role of a therapist. Both active free-speech interactions lasted for around five minutes each. To obtain a baseline measurement, all participants were also exposed in the neutral virtual world (watching a video of mountain animals) at the beginning of the experiment for about three minutes. The experiment had a within-subject design and the order of two active free-speech interactions was counterbalanced. To measure the physiological data, participant's heart rate was recorded during the exposure. Furthermore, at the end of each session, data were collected on the self-reported anxiety and feeling of presence. Both the level of self-reported anxiety and heart rate proved to differ significantly between the three virtual scenarios.

Based on these results of the first study, a second study was formulated. In this second study, a group of 24 non-patient participants (different group than the first study) were recruited. All participants were exposed to three different experiment conditions, starting with a neutral virtual world, where after they were exposed to a positive and a negative job interview condition. The virtual job interview has a similar setup as the first study, however, the difference was the duration and the dialogue content. The dialogue interaction not only lasted longer (around 16 minutes), but also had two different styles of dialogue; a positive and a negative style, where the ratio of the dialogue style was manipulated. The negative interview was broken up into four consecutively slots. In each slot the ratio of negativity of the dialogue style increased, starting from 50%, moving up to 75%, and finally to 100%. In the last slot it returned back to 50% again. In the positive condition this progress was mirrored. Here the ratio of negativity decreased in each slot, starting from 50%, lowering to 25%, and finally to 0%. In the last slot the ratio moved back to 50% again. Each slot lasted around four minutes. The second study was set up as a double-blind experiment using a within-subject design. A questionnaire

measured the participants' feeling of presence, their dialogue experience with virtual humans, their interview experience, and their perception towards the virtual human. The length of participants' answer during the exposure were also recorded and analyzed to measure the avoidance behaviour. Moreover, the participant's self-reported anxiety was automatically collected as well as his or her heart rate. The designs, methods, results and conclusions drawn from both studies are discussed in *chapter 3*.

The ***third hypothesis***, regarding the automatic anxiety regulation, was empirically studied in an experiment with a group of 24 non-patient participants. The main part of the experiment consisted of three sessions: a calibration session, followed by a first session and a second exposure session. The calibration session was intended to create a personalized anxiety measure and to align this measure with a standard scale. This procedure used imaginary exposure. The calibration session lasted for around four minutes and every minute participants' self-reported anxiety and heart rate were recorded. In the first and second session, all participants were exposed to two different types of system response conditions: (1) a static system response condition where the level of stressors remain constant, and (2) a dynamic system response condition where the level of stressors adjusted automatically with the aim to keep anxiety levels of participants at a constant level. Both sessions involved a job interview scenario that lasted around 16 minutes involving again a free-speech dialogue with a virtual human. The experiment had a within-subject design. During the exposure sessions participants' heart rate and heart rate variability were recorded, as well as the self-reported anxiety and their answer length. A detailed description of anxiety regulation mechanism, calibration procedure and multi-modal anxiety measurement is presented in *chapter 4*. This chapter also presents a detailed analysis on the effectiveness of the anxiety regulation mechanism itself.

The ***feasibility question*** about a home-based VRET system was addressed by designing and implementing such a system. Here three important key techniques were identified: (1) dialogue techniques to create extensive free-speech dialogue interactions between a patient and a virtual character in the virtual world automatically; (2) patient's automatic anxiety regulation; and (3) the development of an intelligent virtual health agent as a patient companion to educate and to motivate him or her during the therapy session. The implemented system resulted in a home-based VRET system, which incorporated 19 different virtual reality social scenarios such as visiting a doctor, having a job interview, meeting a blind date in a restaurant, talking to a stranger at a bus station, buying a t-shirt, meeting a stranger at a party. Furthermore, a therapist application was also developed as a standalone application used by therapists to interact with their patients, for example, registering a patient into the system, creating a personalized treatment plan, exchanging secure communication via an e-mail-based platform, monitoring a patient's progress during the treatment by evaluating the self-reported anxiety, heart rate and questionnaires' result, writing a personal log-book for each patient, and creating and adjusting the treatment schedule. A secure and centralized remote database server was also developed and established to support the interaction as well the communication between therapist, patient and intelligent virtual coach.

The system was evaluated in a pilot study with five social phobia patients who met DSM-IV criteria for generalized social anxiety disorder. During the pilot study, each pa-

tient was scheduled to receive 10 treatment sessions at his or her home. Patients' self-reported anxiety and heart rate were recorded during VR exposure to measure the level of anxiety. A comprehensive discussion of the home-based VRET design system and the evaluation of the pilot study can be found in *chapter 5*.

Finally, the conclusions that can be drawn and the limitations of the work presented in this thesis are discussed in *chapter 6*. Here also the scientific and the practical contributions of the work are discussed, and suggestions are made for future research.

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2

AUTOMATIC MECHANISMS FOR MEASURING SUBJECTIVE UNIT OF DISCOMFORT

Current practice in Virtual Reality Exposure Therapy (VRET) is that therapists ask patients about their anxiety level by means of the Subjective Unit of Discomfort (SUD) scale. With an aim of developing a home-based VRET system, this measurement ideally should be done using speech technology. In a VRET system for social phobia with scripted avatar-patient dialogues, the timing of asking patients to give their SUD score becomes relevant. This study examined three timing mechanisms: (1) dialogue dependent (i.e. naturally in the flow of the dialogue); (2) speech dependent (i.e. when both patient and avatar are silent); and (3) context independent (i.e. randomly). Results of an experiment with non-patients (n=24) showed a significant effect for the timing mechanisms on the perceived dialogue flow, user preference, reported presence and user dialog replies. Overall, dialogue dependent timing mechanism seems superior followed by the speech dependent and context independent timing mechanism.

***Keywords**: Virtual Reality exposure therapy, social phobia, anxiety level measurement, SUD score, speech recognition, speech detector.*

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2.1. INTRODUCTION

SOCIAL phobia is an anxiety disorder, where individual fear to do or say something in front of others that will be perceived as humiliating or embarrassing. The disorder is one of the most often occurring anxiety disorders, with reports that estimate this to affect 13.3% of the US population [1], 6.7% of European population [2], and 9.3% of Dutch population [3] during their live. The effect of this phobia on patients includes secondary depression and substance abuse (e.g. alcoholism, drug abuse), restricted socialization (e.g. professional, romantic and everyday informal social interaction), and poor employment and education performance [3]. Social phobia sufferers have a strong fear of social situations, such as talking in public, making a phone call, entering room with other people, ordering food in the restaurant, starting a simple conversation with strangers, etc.

The gold standard for treatment of social phobia is exposure *in vivo*, where patients are gradually exposed to these social situations. One significant limitation of exposure *in vivo* is the difficulty for the therapist to get adequate and controlled social interactions (e.g. arrange the audiences, setup specific situation, etc.). Virtual Reality (VR) can overcome many of the shortcomings of *in vivo* exposure; in addition it provides a treatment that is more readily accepted by clients [4, 5].

During an exposure session, therapists normally ask patients about their anxiety level often using the Subjective Unit of Discomfort (SUD) score instrument [8]. SUD is a scale from zero ("no anxiety at all") to 10 ("the highest level of anxiety that you can imagine") measuring the subjective intensity or level of anxiety the individual is experiencing. With the aim of developing a home-based VRET system, where the system can be used for home treatment in which the patient can perform self-treatment without intensive therapist supervision, this measurement ideally should be done automatically using speech technology. However, with a VRET system for the treatment of social phobia, patients might be involved in a dialogue with an avatar in a virtual environment.

Since the SUDs measurement is done automatically with speech technology, a key question becomes the timing of asking for a SUD score as unexpected interruption might negatively affect patients' experience in a given situation, since poorly timed interruptions can adversely affect task performance [9, 10] and emotional state [11] of the users. To study the proper timing of asking participants to rate their SUD score in the dialogue-based virtual world, three proposed timing mechanisms were examined: (1) dialogue dependent (i.e. naturally in the flow of the dialogue, e.g. just before the start of a new avatar questions), (2) speech dependent (i.e. when both patient and avatar are silent), (3) context independent (i.e. randomly, but in this study when the patient is talking, testing a worst case interruption scenario).

2.2. METHOD

TO study the proper timing of asking participants to rate their SUD score, 24 participants (11 females) were recruited in the study that was approved by the university ethics committee. The age of the participants ranged from 23 to 39 years (M = 30.3, SD = 4.7). All participants had a university background (current master and PhD students). Further, all participants had seen 3D stereoscopic images or movies, and none of them

reported to have been exposed to virtual reality before. At the start of the experiment participants received a short introduction about the overall aim of the study and signed a consent form. After this, they completed the Personal Report of Confidence as a Public Speaker (PRCS) and the basic information questionnaire. Subsequently, speech recognizer was trained.

The main part of the experiment consisted of three sessions with the virtual audience of avatars, talking about three out of four different topics (chosen randomly from the following topics: Democracy, France, Dogs and Penguins [4]). To help them during the initial 3 minutes presentation about the topic, they were provided with a sheet containing some general pointers to talk about, which did not overlap with the question sets of the avatars. The presentation phase lasted 2 to 3 minutes, after which avatars started the question and answer phase, which lasted around 1 to 2 minutes. All participants were exposed in a virtual environment using the Delft Remote Virtual Reality Exposure Therapy (DRVRET) system [7] extended with implementation of the three different dialog timing interruption mechanisms for automatic SUD measuring.

The DRVRET system architecture was customized with speech recognition and a speech detector engine interface. The speech recognition engine decodes andrecognizes the speech from patients and then processes this further. In the current setup, DRVRET used Microsoft SAPI (Speech Application Programming Interface) 5.4 based on Windows 7 combined with the SPINX speech engine interface as its main speech engine. Speech detector functioned as a Voice Activity Detection, a technique used in DRVRET speech processing in which the presence or absence of human-avatar speech is detected. The software package Vizard was used for the visualization of the virtual room and avatars. Animations for avatars were done using 3D Studio Max using key frame method. The hardware used was a Dell Precission T3400 with Intel quad core Q6700 @ 2.66 Ghz, 4 GB of RAM, with NVidia Geforce Quadro FX 4600 graphic card running on Windows 7 x64 bit and a Toshiba Satellite L300 laptop running on Windows 7 x32 bit. Participants sat behind a table equipped with microphone, facing a 3.5 by 2.5 meters virtual room projected with a screen resolution of 1280 x 1024 pixels at about two meters distance.

The experiment used a within-subject design and the order of three timing mechanism conditions was counterbalanced. In each session, participants were asked to complete the Igroup Presence Questionnaire (IPQ) [14], the Dialogue Experience Questionnaire (DEQ) [12] and the specially-designed questionnaire for this study to measure participants' experience after answering automatic SUD score questions: the SUD Score Experience Questionnaire (SEQ). During each exposure session participants were asked two to four times to rate their anxiety by giving SUD scores, depending on actual course of the dialogue between avatars and the participant.

2.3. RESULTS

To study the effects of the timing mechanisms a series ANOVAs with repeated measures were conducted (experiment data and R-scripts were available online at 4TU Centre for Research Data*). A significant effect was found in the total SEQ score ($F(2,46) = 1065.24$; $p < 0.001$) and total DEQ score ($F(2,46) = 628.96$; $p < 0.001$). The total SEQ

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Table 2.1: Mean (*SD*) of measure for three timing mechanism.

Measure	Dialog Dependent	Speech Dependent	Context Independent
Total SEQ**	5.1 (0.6)	18.9 (2.2)	26.3 (2.0)
Total DEQ**	172.6 (3.3)	163.0 (4.5)	141.4 (4.0)
Total IPQ*	42.2 (3.5)	42.6 (3.5)	42.8 (3.5)

* $p < 0.05$; ** $p < 0.001$

Table 2.2: Mean, Median (IQR) and Interobserver agreement of the relative frequency for five dialog replies in three conditions.

Measure	Dialog Dependent	Speech Dependent	Context Independent	Interobserver agreement (*r*)
Details answer	0.31, 0.23 (0.43)	0.23, 0.17 (0.23)	0.18, 0.18 (0.29)	0.72 – 0.88
Normal answer*	0.40, 0.31 (0.55)	0.31, 0.29 (0.52)	0.29, 0.23 (0.43)	0.81 – 0.91
Simple/ short answer	0.23, 0.16 (0.26)	0.30, 0.28 (0.43)	0.21, 0.23 (0.18)	0.75 – 0.84
"Don't know" answer	0.06, 0.00 (0.00)	0.16, 0.00 (0.25)	0.16, 0.00 (0.29)	0.93 – 0.98
"Lost in the dialog" **	0.00, 0.00 (0.00)	0.00, 0.00 (0.00)	0.16, 0.00 (0.27)	0.95 – 0.98

* $p < 0.05$; ** $p < 0.001$

score (Table 2.1) suggests that participants rated the dialogue dependent timing mechanism as less interruptive than the speech dependent timing mechanism and the latter was again rated as less interruptive as the context independent timing mechanism.

The total DEQ score showed a similar pattern with regard to the dialogue experiences. Yet, an opposite pattern was found in the total IPQ score ($F(2,46) = 4.05$; $p = 0.024$). Participants rated presence highest for the context independent timing mechanism, while again the speech dependent in the middle and lowest for dialogue dependent timing mechanism. This might be a side effect of the phenomenon called Breaks In Presence [13] that participants might have experienced during the exposure, which occurs when they become aware of another reality. A possible explanation could be that the severity of the interruption made participants more aware of the break in presence switching from the virtual world to real world to answer SUD score questions, and back again to virtual world. Participants might have taken the intensity of break in presence as a sign of feeling present in the virtual world.

During the experiment audio recordings were made of the dialogues between avatars and participants. To understand the effect of the interruption for SUD score the analysis of the recording focused on how the participants continue to talk with the avatars after they had given their SUD score. The participants' replies were coded with the following five labels: (1) detail answer, (2) normal answer (3) simple/short answer (4) "do not know" answer and (5) "lost in the dialog" answer. This resulted in five separate measures; each representing for a session the relative frequency of participants' replies that were coded with a specific label. With this coding scheme, three coders coded the audio recordings independently. Interobserver agreement was evaluated with Pearson's correlation analysis, showing (Table 2.2) acceptable agreement as all correlations were larger than 0.7 (all $p < 0.01$).

To test the overall effect of the timing mechanism on the participants' dialog replies, a series of Friedman test were conducted, using the five relative frequency measures as

dependent measures (Table 2.2). No significant effect was found for the timing mechanism on participants' replies in the detail answer, simple/short answer and "don't know" answer measures. However, a significant effect was found in the normal answer ($\chi^2(2) = 6.20$, $p = 0.045$) and "lost in the dialog" answer ($\chi^2(2) = 22.00$, $p < 0.001$) measures. For more detailed analysis, paired comparisons with Wilcoxon Signed-Rank Tests were conducted on these two measures. In the normal answer, only a difference between dialog dependent and context independent ($Z = -1.89$, $p = 0.059$) timing mechanism was found that approached the significant level of .05. Furthermore, in the "lost in the dialog" answer, significant differences were found between speech dependent and context independent ($Z = -2.95$, $p = 0.003$), and between dialog dependent and context independent ($Z = -2.95$, $p = 0.003$) timing mechanism.

2.4. DISCUSSION AND CONCLUSION

THE results of the experiment seem to suggest that the automatic timing of asking participants to rate their SUD score could affect their subjective experience and their behavior in a dialogue-based virtual world. Although potentially more development intensive, in-cooperating the moment of asking for SUD score into the flow of the dialogue out performs other timing mechanism such as speech dependent and context independent timing mechanisms. Future research is needed to replicate these finding with social phobic patients. These findings can help developers to re-advance current VRET systems by implementing speech-recognition-based SUD score assessment, a feature especially relevant in future home-based VRET systems equipped with automatic feedback loop control system.

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3

CONTROLLING SOCIAL STRESS IN VIRTUAL REALITY ENVIRONMENTS

Virtual reality exposure therapy has been proposed as a viable alternative in the treatment of anxiety disorders, including social anxiety disorder. Therapists could benefit from extensive control of anxiety eliciting stimuli during virtual exposure. Two stimuli controls are studied in this study: the social dialogue situation, and the dialogue feedback responses (negative or positive) between a human and a virtual character. In the first study, 16 participants were exposed in three virtual reality scenarios: a neutral virtual world, blind date scenario, and job interview scenario. Results showed a significant difference between the three virtual scenarios in the level of self-reported anxiety and heart rate. In the second study, 24 participants were exposed to a job interview scenario in a virtual environment where the ratio between negative and positive dialogue feedback responses of a virtual character was systematically varied on-the-fly. Results yielded that within a dialogue the more positive dialogue feedback resulted in less self-reported anxiety, lower heart rate, and longer answers, while more negative dialogue feedback of the virtual character resulted in the opposite. The correlations between on the one hand the dialogue stressor ratio and on the other hand the means of SUD score, heart rate and audio length in the eight dialogue conditions showed a strong relationship: $r(6) = 0.90$, $p = 0.002$; $r(6) = 0.74$, $p = 0.036$ and $r(6) = -0.91$, $p = 0.002$ respectively. Furthermore, more anticipatory anxiety reported before exposure was found to coincide with more self-reported anxiety, and shorter answers during the virtual exposure. These results demonstrate that social dialogues in a virtual environment can be effectively manipulated for therapeutic purposes.

***Keywords**: Virtual Reality Exposure Therapy (VRET), dialogue stressor, feedback response, social phobia, social scenes, embodied virtual agent.*

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3.1. INTRODUCTION

SOCIAL anxiety disorder, also commonly referred as social phobia, is one of the most prevalent mental disorders [1]. People with social phobia experience a strong fear of being judged negatively by others and of being embarrassed in social situations (e.g., talking to other people or eating or drinking in front of other people). The gold standard to treat patients with social phobia is cognitive behaviour therapy with the central component being gradual exposure *in vivo*, whereby patients are gradually exposed to anxiety provoking real-life situations until they habituate to the anxiety provoking social situations. Although exposure in vivo is an effective treatment for most patients, it is also associated with some limitations, such as the limited therapeutic control over different aspects of exposure and a relatively high number of drop outs as some patients are not willing to get exposed to feared situations [2-4].

Virtual Reality Exposure Therapy (VRET) has been proposed as an effective alternative to overcome these shortcomings of exposure *in vivo* [5-9]. Exposure in virtual reality (VR) makes the control of exposure elements more manageable since the patient is exposed in a controlled Virtual Environment (VE) where the parameters of anxiety evoking stimuli can be changed and manipulated by the therapist. Current VRET systems used for social phobia patients mainly focus on recreating a social scene setting, such as public speaking scenarios, clothing shops, public transport, or restaurants. At the start of the treatment, an anxiety hierarchy of anxiety-arousing social situations is established. This hierarchy is then used to order the VR situations the patient will be gradually exposed to, starting with less anxiety-arousing situations and eventually moving to more anxiety-arousing situations as treatment progresses.

Even though several studies [3,4,10,11] have reported promising initial efficacy findings for VRET for social phobia, the used VR systems mainly allow the therapist to control social anxiety only by moving between different VR situations. Hence during the actual exposure in the VR situation, the therapist has limited ability to introduce or remove anxiety-evoking stimuli in a VR world. Based on research on other anxiety disorders, this ability might prove useful for the treatment of social phobia as well [12]. For example, in VRET for fear of flying, a therapist is given the opportunity to make relevant changes of the virtual world in use if appropriate, such as switching on the sign *fasten your seatbelts*, flying under different weather conditions, or letting the pilot make a specific announcement [13]. In VRET for fear of heights, the therapist can move patients to a higher step of a virtual staircase, or place them closer to the edge of a balcony [14]. With regard to VRET for social phobia, however, little attention has been given to this aspect of the treatment. We argue that manipulating the dialogue between the patient and a virtual character can increase the efficacy of VRET for social phobia. For example, by having the virtual character responding on the behaviour of the patients in the dialogue, the therapist can directly address the fear of being evaluated negatively by others.

Affective feedback plays a key role in dialogues between humans, and can elicit for example defensive or supportive listener's feedback responses [15]. Furthermore, the listener can in turn actively influence the emotional state of the speaker, as is fundamental to empathic listening technique [16]. In the long term, human interaction influences individuals' self-esteem as it feeds into their reflected appraisal process [17], i.e. the way they imagine how other people see or judge them [18].

Furthermore, a conversation between a human and virtual characters, which mirrors a role-play between human and human dialogue conversation, can influence the emotional state of the human, as has been demonstrated in prior research with VR systems [19,20]. Yet, the emotion manipulation and evaluation of the stressor stimuli until now has always covered the entire conversation and has not been directed at isolated sections within a conversation. Accordingly, the aim of this study was to investigate whether it is possible to induce anxiety in a virtual environment by manipulating the dialogue feedback responses between a human and virtual characters as this could benefit VRET.

3.2. RELATED WORK

FOR exposure in vivo, therapy manuals [21] often suggest scenarios that include social interaction, i.e. a dialogue with other individuals, for example, asking multiple people for directions to an obvious location, asking a person at a bar whether he has seen a specific movie and asking if he knows the main actors in the movie, renting a DVD and immediately asking your money back as you do not have a DVD player. When it comes to exposure in virtual reality, most studies focus mainly on public speaking scenarios [2,11,22-24]. However, in recent studies, other social scenarios have also been successfully developed, such as a restaurant scenario [25], interaction inside public transport [10], clothing store [26], train and bus station [25,26], a bar scenario [10,27], formal job interview [26,28] and a blind date scenario [26]. These VRET systems allow therapists to use a variety of virtual social scenes to expose patients to different social situations thereby following the order set by the fear hierarchy. Some patients however might feel unable to conduct exposure, or opposite, do not experience enough anxiety or discomfort. In these cases therapist manuals [21] for exposure *in vivo* advise therapists to show an adequate degree of flexibility and modify the exposure accordingly, e.g. change the topic of the presentation, bring in new audience members, or interrupt the patient at various points in their presentation. The aim is to establish an optimal level of anxiety during the anticipation phase of exposure. For example, some manuals [21] have even suggested as a general rule to have an anxiety level of somewhere between 5 and 7 on an 11-point scale from 0 (no anxiety) to 10 (extreme anxiety). However, this level might be very much patient dependent.

For exposure in virtual reality, flexibility has been sought in changing the body posture of the members of a virtual audience [29], eye gaze of the virtual character [26,28], distance between virtual character and the patient [30,31], the facial expression [30,32], attitude [29,33] or personality [26,34] of the virtual character. However, less research attention has been devoted to control the verbal element of the interaction, i.e. the content of the dialogue. Most VRET systems that recreate social situations provide no or only limited verbal responses of the virtual character, while there is clear support that humans respond in a similar manner to a computer that acts as social actor as they would do when interacting with other humans [19,32,35,36]. Some have also studied this phenomenon in the context of dialogues with virtual humans. This has been done not only to study social anxiety [26,29,30], specifically public speaking anxiety, but also schizophrenia [31]. For example, Ku et al. [31] demonstrated that virtual humans could engage schizophrenic patients with limited dialogue only. Slater et al. [20] demonstrated that people were aroused when virtual humans communicated with them. They found

that people with more social anxiety also experienced more stress compared to people with less social anxiety when engaged in an active conversation with virtual humans. Using semi-scripted conversations and speech recognition, ter Heijden and Brinkman [37] showed that it is possible to create 5 minute elaborate conversations between the patients and virtual humans in virtual reality as part of a question and answer session after a small presentation. The use of semi-scripted conversations has now also been used to recreate conversations in other social situations such as having a conversation with a stranger at a bus stop, buying a t-shirt, a bra or baby clothes in a shop and dining with a blind date [26].

Virtual humans have also been used for educational purposes. Interestingly, here the effect of feedback has been studied. For example, receiving positive instead of negative feedback from a digital assistant can speed up the students learning time [38,39]. Also pedagogical agents that give positive or empathic feedback can enhance the student's interest in a topic and their self-efficacy [40,41]. As social situations in virtual reality with relative long dialogue interaction provide multiple opportunities to give patients positive or negative feedback, it would be an ideal phobic stressor for a VRET system. Another major advantage is that the situation can be changed while the patient is being exposed. This would give the therapist non-interruptive intervening possibilities to get the patient's anxiety to an ideal level for exposure to work. Hence, this paper presents two studies that examine the following hypotheses underlying this idea:

H1: *Different social dialogue situations are able to elicit different levels of anxiety.*

H2: *In a social dialogue situation, the ratio of positive and negative responses from a virtual human proportionally affects the human anxiety level whereby a dialogue with mainly negative responses elicits more anxiety than a dialogue with mainly positive responses.*

H3: *After a dialogue with a virtual human that contained responses mainly of one affect polarity, anxiety will change correspondingly if the dialogue continued with fewer response of this affect polarity. In other words, the level of anxiety can be controlled on-the-fly by manipulating the dialogue polarity.*

H4: *Individual's degree of social anxiety is positively related to the amount of elicited anxiety when exposed to a dialogue stressor.*

3.3. METHOD (FIRST STUDY: SOCIAL SCENE EXPERIMENT)

3.3.1. ETHICS STATEMENT

The first study was approved by Delft University of Technology Human Research Ethics Committee. Prior to the experiment, written informed consent was obtained from all participants. Furthermore, for publication policy, the individual in this manuscript has also given written informed consent (as outlined in the PLOS consent form) to publish case details. After the experiment, participants received a chocolate bar and drink (tea, coffee or warm chocolate) as a token of appreciation for their participation.

Figure 3.1: Setup of the experiment

3.3.2. EXPERIMENT DESIGN

In order to study the effect of various VR scenes on anxiety level, a within-subjects experiment was conducted. Figure 3.1 depicts the experimental setup. All participants were exposed to three different VR scenarios: a neutral virtual world [42] where participants were seated in front of a television showing a documentary about wildlife (Figure 3.2 (a)), a blind date (Figure 3.2 (b)), and a job interview session with virtual humans (Figure 3.2 (c)).

3.3.3. PARTICIPANTS

Sixteen participants (5 females and 11 males) were recruited in the first experiment that was approved by the ethics committee of Delft University of Technology. Fourteen participants were recruited from Delft University of Technology and two from Utrecht University. The age of the participants ranged from 19 to 27 years ($M = 22.44$, $SD = 2.42$). All participants reported to have seen 3D stereoscopic images or movies, yet none of them reported to have been exposed to virtual reality environments before. Furthermore, all participants were naïve with respect to the hypothesis.

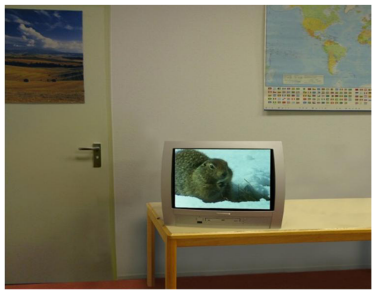
3.3.4. MEASUREMENTS

SUD SCORE

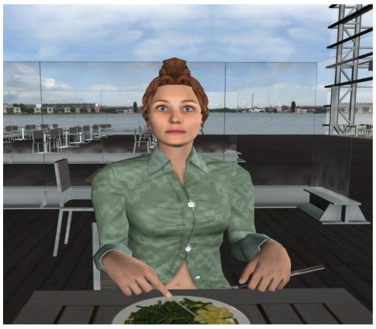
The levels of anxiety in the virtual environments were measured with the Subjective Units of Discomfort (SUD) developed by Wolpe [43]. The SUD scale measures levels of anxiety on a scale from zero ("no anxiety at all") to 10 ("the highest level of anxiety that you can imagine").

PRESENCE

Sense of presence in the virtual reality environment was assessed with the Igroup Presence Questionnaire (IPQ) developed by Schubert et al. [44]. The IPQ is composed of 14 items rated on a seven-point Likert scale. The scores on the 14 IPQ items are mapped



(a)



(b)

(c)

Figure 3.2: Virtual neutral world (a), virtual blind date (b) and virtual job interview (c)

onto three subscales, namely *Involvement* (the awareness devoted to virtual environment), *Spatial Presence* (the relation between the virtual environment and the physical real world), and *Experienced Realism* (the sense of reality attributed to the virtual environment). IPQ also contains one item that assessed participants' general feeling of being in the virtual environment.

HEART RATE

It was expected that the heart rate would increase if people were feeling anxious in a daunting or frightening situation. To measure the elicited fear responses in this experiment, heart rate of the participants was monitored continuously. The heart rate was recorded with a Mobi8 device from TMSI with an Xpod Oximeter. The participant inserted a finger into an adult articulated finger sensor.

3.3.5. PROCEDURE AND APPARATUS

At the start of the experiment participants received a short introduction about the overall aim of the study and filled in a basic questionnaire about their age, education and signed a consent form. Participants were not informed about the different VR scenario conditions.

The main part of the experiment consisted of three different VR scenarios, one passive interaction with neutral VR world and two active free speech interactions with virtual humans (Figure 3.2 (b) and (c)). To control for possible learning effect, the order

of the two active interaction scenarios (conditions) was counter balanced. A baseline measurement was obtained by exposing participants to the neutral VR world. This also allowed them to become familiar with the VR exposure. This session lasted for two minutes and at the end of the session participants were asked to rate their SUD score. In the other conditions, participants had two sessions (five minutes each) active free speech interaction with a virtual human in VR. The two VR social scenes that were used in the experiment were: (a) meeting a blind date in a musical building's restaurant (where the virtual blind date's gender was adapted for participants' gender) and (b) having a job interview for a restaurant server position. Job interview and blind date scenes were selected as relevant social scenes to elicit social anxiety since both social scenes are often suggested for in-session exposures in the cognitive-behavioural group therapy [45]. At the end of this session, participants were asked to rate their SUD score. After these two sessions, participants filled in the IPQ. The entire experiment took about 25 minutes.

All participants were exposed to a virtual reality environment using the Delft Remote Virtual Reality Exposure Therapy (DRVRET) system [26]. This system allows participants to engage in a free speech dialogue with virtual characters while being monitored by a therapist, in this case the therapist was replaced by the researcher. Both, the blind date and the job interview scenes contained between 35-50 pre-recorded sentences, which the researcher could use to let the virtual human respond to the participants' answer or comment with the aim of engaging the participants in to a 4 to 5 minutes conversation. As a fallback strategy, each dialogue also has a number of dialogue independent responses, which could be used in case the participants' answer or comment did not match one of the dialogue dependent responses. To avoid an ever widening dialogue tree, as each virtual character response can move the dialogue into new directions, the dialogues were written in such a way that they merged back into the dialogue's main story line [37].

The software package Vizard v3.0 was used for the visualization of the virtual room and virtual human. Animations for virtual humans were created using 3D Studio Max using a keyframe method. The hardware used was a Dell Precision T3400 with Intel quad core Q6700 @ 2.66 Ghz, 4 GB of RAM, with NVidia Geforce Quadro FX 4600 graphic card running on Windows 7 x64 bit as patient's computer and a Toshiba Satellite L300 running on Windows 7 x32 bit as therapist's computer. Participants sat behind a table equipped with a microphone and wore the eMagin Z800 Head Mounted Display (HMD) on 800 x 600 pixels resolutions, with 40 degrees diagonal Field of View, and built-in 3DOF tracker tracked at a 125 Hz update rate and the sound was played through desk-mounted speakers.

3.3.6. RESULT

In order to analyse the data (experiment data and R-scripts were available at 4TU Centre for Research Data*), a series of multivariate and univariate analyses were conducted. Where the sphericity assumption was violated a *Greenhouse-Geisser* correction was applied. To control for possible inflations of Type I Error, *post-hoc* analyses were conducted with Sidak correction.

To get a general understanding of the experienced presence level and to examine

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Table 3.1: Comparison between different conditions on SUD score and heart rate

Measurement		*M1(SD)*[a]	*M2(SD)*[b]	*t*	*df*	*p*
Condition 1	**Condition 2**					
SUD score (0-10)						
Neutral	Blind date	2.38 (0.89)	3.69 (1.01)	-5.55	15	< 0.001
Neutral	Job interview	2.38 (0.89)	4.56 (1.03)	-7.89	15	< 0.001
Blind date	Job interview	3.69 (1.01)	4.56 (1.03)	-3.42	15	0.011
Heart rate (bpm)						
Neutral	Blind date	77.2 (11.13)	81.2 (11.30)	-5.7	15	< 0.001
Neutral	Job interview	77.2 (11.13)	84.1 (11.03)	-5.72	15	< 0.001
Blind date	Job interview	81.2 (11.30)	84.1 (11.03)	-2.7	15	0.048

[a] *Mean and standard deviation of condition 1*
[b] *Mean and standard deviation of condition 2*

whether the virtual world in this experiment established a reasonable level of presence to evoke the anxiety, the overall IPQ score was compared to the online IPQ data set (downloaded on February 9th, 2013. For comparison data see: http://www.igroup.org/pq/ipq/data.php) for stereo HMD visual stimuli. The overall IPQ rating (M = 52.44, SD = 3.05) in this experiment was significantly higher ($t(40.98)$ = -4.64, $p < 0.001$) than the overall IPQ online data set (M = 38.93, SD = 17.09), which suggest that the participants were more immersed than the level reported in other virtual worlds.

In order to test the overall effect of different social scenes on levels of anxiety (H1), a repeated-measures MANOVA was conducted, with different social scenes (neutral VR world, virtual blind date and virtual job interview) as the independent within-subjects variables. The SUD score and heart rate were used as dependent variables. The results showed a significant effect of different virtual social scenes on anxiety levels, ($F(4,12)$ = 19.14, $p < 0.001$, $\eta^2 = 0.87$). Furthermore, univariate analyses found significant effects ($F(2,30) = 36.65$, $p < 0.001$, $\eta^2 = 0.71$) on the SUD score and heart rate ($F(2,30) = 23.08$, $p < 0.001$, $\eta^2 = 0.61$).

Next, *post-hoc* tests with Sidak correction were performed on the SUD score rating and heart rate in all three conditions. The results are presented in Table 3.1. Both, exposure to the blind date scene and the job interview scene were associated with significantly higher SUD levels. Furthermore, exposure to the job interview scene was associated with higher SUD levels than exposure to the blind date scene. A similar pattern was found in the heart rate measurement, participants' heart rate in the job interview scene was higher than in the blind date scene and the participants' heart rate in the blind date scene was again higher than in the neutral VR world.

3.3.7. DISCUSSION

The goal of this experiment was to investigate whether exposure to various social scenes in virtual reality is associated with different levels of anxiety (**H1**). Our results based on subjective as well as objective measurements of anxiety yielded that as the social scene changed from the neutral VR world to the blind date scene or the job interview scene, the participants' anxiety level significantly increased, which suggests that these various VR scenes could evoke different levels of anxiety. This indicates that virtual environments involving interactions between participants and virtual human (avatars) can be used to

elicit anxiety among this group of participants.

This first study showed that our virtual social worlds can be used successfully to provoke levels of anxiety. In order to examine the association between different characteristics of the content of the dialogue and levels of social anxiety, the second study was conducted.

3.4. METHOD (SECOND STUDY: DIALOGUE STRESSOR EXPERIMENT)

3.4.1. ETHICS STATEMENT

The second study was approved by Delft University of Technology Human Research Ethics Committee. Prior to the experiment, written informed consent was obtained from all participants, which also included their agreement to publish their (dialogue interaction) data with avatars in an anonymous fashion. After the experiment, participants received a chocolate bar and drink (tea, coffee or warm chocolate) as a token of appreciation for their participation.

3.4.2. DIALOGUE STRESSOR

The social scene selected for the second experiment was a job interview, which consisted of a question and answer session. This VR selection was based on the first experiment result, where the job interview VR elicited more anxiety compared to the blind date VR. Each of dialogue unit in the job interview VR was defined as: [**virtual human's question**] → [**participant's answer**] → [**virtual human's response comment**]. Each unit started with the virtual human posing a question related to the vacancy for which the participant had applied. The next block in the unit was the participant's answer to this question, which was followed by the last unit block, the virtual human's comment on that answer.

In order to influence anxiety levels, this dialogue unit could either be positive or negative. For example, the positive dialogue style consisted of a set of friendly, positive tone and enthusiastic type of questions and response comments, for example *"Why do you want to work for our company?"* and ended with the virtual human comment *"A very good reason indeed! I can see and feel a lot of passion in you!"* in reaction to the participant's answer. On the other hand, the negative dialogue unit consisted of a set of unfriendly, negative tone, unenthusiastic and critical types of questions and responses, for example, *"Are you sure you want to work for our company?"* and ended with a virtual human's comment *"That's all? Nothing else? Seems as though you're not so serious about working here!"*. A more comprehensive example of a typical dialogue interaction between a participant and an avatar as observed in the experiment is shown in the **Appendix A**.

A dialogue database was created with a set of 95 positive dialogue units and a set of 95 negative dialogue units. The hypothesis was that the ratio by which an individual was exposed to a negative, instead of a positive dialogue unit, is correlated with his or her anxiety scores. Stated differently, it was expected that a dialogue stressor can induce anxiety levels.

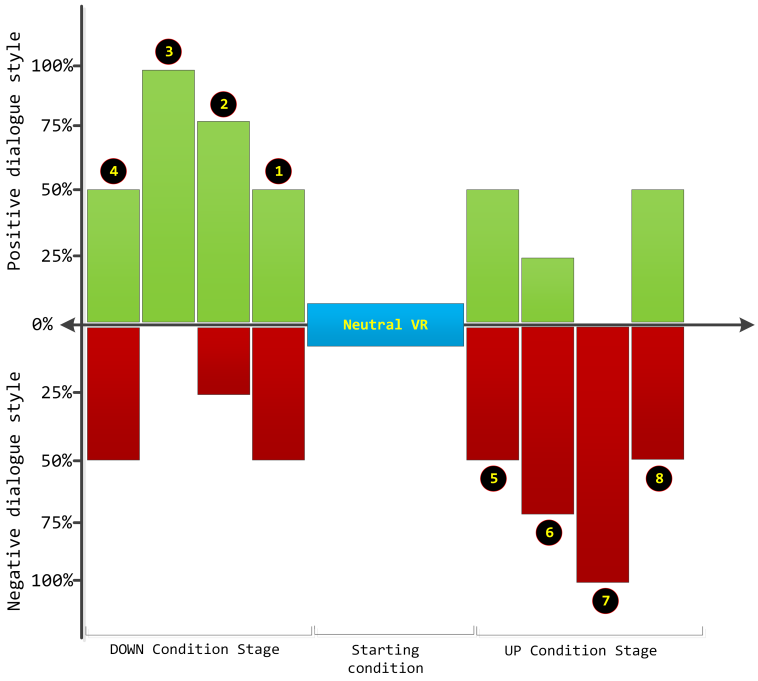

Figure 3.3: Two conditions that consist of eight dialogue stressor sub-conditions in the experiment

3.4.3. EXPERIMENT DESIGN

The experiment was set up as a within-subjects design. All participants were exposed to 8 dialogue stressor sub-conditions (illustrated in Figure 3.3), divided into two main conditions: positive condition and negative condition. These sub-conditions were created by manipulating the ratio of positive and negative dialogue units to which individuals were exposed to in the job interview. In the positive condition, the experiment started with a 50% negative - 50% positive dialogue ratio slot (C1) then continued to 25% negative - 75% positive dialogue ratio slot (C2), 0% negative - 100% positive dialogue ratio slot (C3) and going down again to 50% negative - 50% positive dialogue ratio slot (C4). On the other hand, in the negative condition, the experiment started with a 50% negative - 50% positive dialogue ratio slot (C5) then continued to 75% negative - 25% positive dialogue ratio slot (C6), 100% negative - 0% positive dialogue ratio slot (C7) and going up again to 50% negative - 50% positive dialogue ratio slot (C8). Each slot lasted four minutes.

The negative condition consisted of more negative dialogue units in the conversations and resulted in a gradual increase of the dialogue stressor to the maximum level (start from C5 to C7), whereas the positive condition produced more positive dialogue units in the conversations that yielded a gradual decrease of the dialogue stressor to the minimum level (start from C1 to C3). The control conditions (C4 and C8) aimed to bring the dialogue stressor levels (whether it was maximum or minimum stressor levels) back to the starting conditions. The aim of these two conditions was to evaluate whether it was possible to control the level of anxiety variables from minimum or maximum stres-

Figure 3.4: Virtual job interview with female (left) and male (right) interviewer

sor level and return the anxiety back to the original state (H3), suggesting extensive control of the phobic stressor.

In order to create specific ratio percentage of dialogue unit slots, the virtual database was created during the *run-time* by the system, hence each participant had 5 set of virtual databases (50% negative dialogue - 50% positive dialogue, 25% negative dialogue - 75% positive dialogue, 0% negative dialogue – 100% positive dialogue, 75% negative dialogue – 25% positive dialogue and 100% negative dialogue – 0% positive dialogue). To make sure that participants were not answering identical question over and over again in the different dialogue conditions, a *question-index pointer* algorithm was used. This algorithm notified the dialogue system to select another question if the question has already been asked in the previous conditions.

To ensure impartiality and to avoid observer bias, the experiment was conducted in a double-blind mode. This meant that neither the participants nor the researcher who remotely controlled the virtual humans' dialogue knew the critical aspects of the experiment (i.e. the dialogue stressor conditions). Furthermore the researcher could also not hear the virtual human as he was in another room where he could only hear the voice of participants over a speaker. The task of the researcher was to click on the questions / comments button when the participants finished their answer. The order of two main conditions and the assignment of the two virtual job interviewers (Figure 3.4) were counter-balanced.

3.4.4. PARTICIPANTS

Twenty-four participants (13 females and 11 males) were recruited in the study that was approved by the ethics committee of Delft University of Technology. The age of participants ranged from 23 to 37 years ($M = 29.38$, $SD = 3.28$). The sample consisted of master and PhD students. Furthermore, all participants had seen 3D stereoscopic images or movies, but only five of them had ever used a virtual reality system before. Hence, all

participants were naïve with respect to the hypotheses.

3.4.5. MEASUREMENT

SUD SCORE

The levels of anxiety in the virtual environments in this study were again measured with the Subjective Units of Discomfort (SUD) [43].

PRESENCE

Sense of being presence in the virtual reality environment was assessed with the Igroup Presence Questionnaire (IPQ) [44].

HEART RATE

The heart rate was recorded with a Mobi8 device from TMSI with an Xpod Oximeter. The participants inserted their finger again into an adult articulated finger sensor.

SOCIAL INTERACTION ANXIETY SCALE (SIAS)

The SIAS [46] was used to evaluate social interactional anxiety and divide participants into groups of higher or lower social anxiety. The SIAS is a 20 items measure on which respondents rate their experiences in social situations associated with social anxiety. The items are rated on a 5-point scale from 0 ("*not at all characteristic or true of me*") to 4 ("*extremely characteristic or true of me*"). The SIAS has been shown to be a reliable measurement of social anxiety [47].

INTERVIEW ATTITUDE QUESTIONNAIRE (IAQ)

The IAQ was designed for use in the current study in order to measure participants' attitudes towards the job interview in the virtual reality. The IAQ is composed of the following six items that were rated on a seven-point Likert scale (from 1 to 7): pleasant – unpleasant (reversed), not relaxed – relaxed, aggressive – not aggressive, uncomfortable – comfortable, polite – impolite (reversed), and energizing – exhausting (reversed). The total IAQ score was calculated by adding up the (reversed) individuals items.

DIALOGUE EXPERIENCE QUESTIONNAIRE (DEQ)

To measure participants' perception of the dialogue quality, e.g. flow, interaction and reality with the virtual human, the DEQ [37] was used. The total DEQ score was calculated by adding up items that were scored on 7-point Likert scale ranging from strongly disagree (1) to strongly agree (7).

PARTICIPANT'S OWN EMOTIONS AND PERCEPTION OF VIRTUAL HUMAN

The Self-Assessment Manikin (SAM) questionnaire was used to measure the participants' own emotion and how they perceived the virtual human's emotion during exposure in virtual reality. The SAM is a non-verbal pictorial assessment technique that measures the amount of pleasure, arousal, and dominance associated with a person's affective reaction to a wide variety of stimuli [48]. Participants rated the dimensions of valence (positive-negative), arousal (excited-calm), and dominance (controlled-in control) via a pencil and paper version. For this experiment, the five-Likert scale manikin figures were taken from PXLab [49].

VERBAL COMMUNICATION EFFECT (BEHAVIOURAL CHANGES)

Patients' speech behavioural changes toward anxiety-provoking situations have been suggested as a variable to determine the level of distress or avoidance behaviour [11,50]. This experiment used an auto-detect speech algorithm [51] to record the total time a participant spoke (in the unit of seconds) during a dialogue slot.

3.4.6. PROCEDURE AND APPARATUS

At the start of the experiment participants received a short introduction about the overall aim of the study and signed a consent form. After this, they completed the SIAS and the basic information questionnaire. The main part of the experiment consisted out of three sessions in the virtual reality world; participant started with exposure in the neutral VR world, after this they were exposed to two job interviews.

To get a baseline measurement and to familiarize the participants with virtual reality, they were exposed to the neutral VR world. This session lasted three minutes. In the other conditions, participants had 16 minutes of active free speech interactions (question – answer session related to the job position for which they had applied) with a virtual interviewer. This session was divided into four slots (Figure 3.3), which consisted of four minutes each and at the end of each slot participants were asked to give a SUD score. At the end of the two interview sessions, participants were asked to complete questionnaires related to the situation that they just experienced i.e. IAQ, DEQ and SAM questionnaires. After these two job interview sessions, participants filled in the IPQ questionnaire. The entire experiment took about 45 minutes.

All participants were exposed to a virtual reality environment using the DRVRET system with the same hardware configuration as the first study (the social scene experiment). The only difference was the HMD; in this experiment a Sony HMZ-T1 HMD was used. This HMD has 1200 x 720 pixels resolutions with 45 degrees field of view and was equipped with a custom-built head tracker using a triaxial gyroscope, an accelerometer and a compass sensors tracked at 6 MHz update rate.

3.4.7. RESULTS

In order to analyse the data (experiment data and R-scripts were available at 4TU Centre for Research Data*), a series of multivariate and univariate analyses were conducted. Where the sphericity assumption was violated a Greenhouse-Geisser correction was applied. To control for possible inflations of Type I Error, *post-hoc* analyses were conducted with Sidak correction.

LOW AND HIGH SOCIAL ANXIETY GROUP

To examine the effect of the dialogue stressor on individuals with less or more social anxiety, the sample was split into two groups; a lower and a higher social anxiety group. These two groups were created based on the SIAS's overall data (M = 25.0, SD = 12.6). Participants who scored below the mean score were assigned to the lower social anxiety group, while the other participants were assigned to the higher social anxiety group.

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Table 3.2: Results of univariate analyses with dialogue stressor as within-subjects factor and social anxiety group as between-subjects factor on SUD score, heart rate and audio length

Factor	Hyp. *df*	Error *df*	*F*	*p*	η^2
SUD score (0-10)					
Dialogue stressors	3.66	80.60	27.66	< 0.001	0.56
Social anxiety group (high and low)	1	22	6.84	0.016	0.24
Dialogue stressors x Social anxiety group	3.66	80.60	5.68	< 0.001	0.21
Heart rate					
Dialogue stressor	1.27	27.85	52.75	< 0.001	0.71
Social anxiety group (high and low)	1	22	2.61	0.121	0.11
Dialogue stressors x Social anxiety group	1.27	27.85	4.14	0.043	0.16
Audio length					
Dialogue stressors	2.87	63.07	168.07	< 0.001	0.88
Social anxiety group (high and low)	1	22	7.24	0.013	0.25
Dialogue stressors x Social anxiety group	2.87	63.07	1.30	0.281	0.06

PRESENCE

Before performing further analyses on the effect of the dialogue stressor on the anxiety level, the reported presence level was analysed. The overall IPQ score was compared to the online IPQ data set (downloaded on February 09th, 2013. For comparison data see: http://www.igroup.org/pq/ipq/data.php) for stereo HMD visual stimuli. The overall IPQ rating ($M = 50.17$, $SD = 5.35$) in this experiment was significantly higher ($t(46.04) = 3.73$, $p < 0.001$) than the overall IPQ online data set ($M = 38.93$, $SD = 17.09$), which suggests that participants in this study were more immersed than the presence level reported in other virtual world. Furthermore, there was no significant difference ($t(22) = 0.35$, $p = 0.733$) found between higher and lower social anxiety groups on the overall level of presence.

ANXIETY LEVEL

In order to test the overall effect of the dialogue stressor conditions on the anxiety level, a doubly MANOVA repeated-measures was conducted, with dialog stressor (C1 to C8) as the independent within-subjects variables and the two social anxiety groups as between-subjects variable. The SUD score, heart rate and audio length were used as dependent variables. The results showed a significant overall main effect of dialogue stressor on anxiety level, ($F(18,5) = 106.01$, $p < 0.001$, $\eta^2 = 1.00$). Furthermore, univariate analyses (see Table 3.2) showed significant effects of dialogue stressor on the SUD score, heart rate and audio length. These results confirm our hypothesis that dialogue stressor can impact anxiety levels (**H2**).

A *post-hoc* test with Sidak correction was performed comparing SUD score, heart rate and audio length in all eight dialogue stressor conditions. The results are presented in Table 3.3. The post-hoc results showed that the participants' overall anxiety level in virtual reality can be controlled up and down on-the-fly (dynamically) by using the dialogue stressor ratio combination. Furthermore, the correlations between on the one hand the dialogue stressor ratio and on the other hand the means of SUD score, heart rate and audio length in the eight dialogue conditions show a strong relationship: $r(6) = 0.90$, $p = 0.002$; $r(6) = 0.74$, $p = 0.036$ and $r(6) = -0.91$, $p = 0.002$ respectively.

Table 3.3: Comparison between dialog stressor on SUD score rating, heart rate (bpm) and audio length (second)

Measurement						
Condition 1	Condition 2	*M1(SD)*[e]	*M2(SD)*[f]	*t*	*df*	*p*
SUD score (0-10)						
50% (end)[a]	0% (C4)[d]	3.88 (0.74)	3.04 (1.27)	-3.75	23	0.006
0%	25%	3.04 (1.27)	3.67 (0.92)	3.32	23	0.018
25%	50% (avg.)[b]	3.67 (0.92)	3.63 (0.84)	-0.28	23	> 0.999
50% (avg.)[b]	75%	3.63 (0.84)	4.42 (1.1)	5.75	23	< 0.001
75%	100%	4.42 (1.1)	5.42 (1.1)	5.54	23	< 0.001
100%	50% (end)[c] (C8)[d]	5.42 (1.1)	4.25 (1.26)	-8.14	23	< 0.001
Heart rate (bpm)						
50% (end)[a]	0% (C4)[d]	82.6 (4.7)	82.3 (3.7)	0.69	23	0.984
0%	25%	82.3 (3.7)	84.5 (5.4)	4.16	23	0.002
25%	50% (avg.)[b]	84.5 (5.4)	85.8 (7.1)	-2.98	23	0.039
50% (avg.)[b]	75%	85.8 (7.1)	90.2 (9.7)	6.83	23	< 0.001
75%	100%	90.2 (9.7)	92.6 (10.2)	-8.84	23	< 0.001
100%	50% (end)[c] (C8)[d]	92.6 (10.2)	92.5 (9.9)	0.46	23	0.998
Audio Length (s)						
50% (end)[a]	0% (C4)[d]	134 (26.0)	177.7 (21.6)	9.7	23	< 0.001
0%	25%	177.7 (21.6)	120 (13)	-16.68	23	< 0.001
25%	50% (avg.)[b]	120 (13)	101.6 (14.1)	7.06	23	< 0.001
50% (avg.)[b]	75%	101.6 (14.1)	71.3 (19)	-10.92	23	< 0.001
75%	100%	71.3 (19)	50.6 (13.8)	6.8	23	< 0.001
100%	50% (end)c (C8)[d]	50.6 (13.8)	82.7 (16.3)	-10.94	23	< 0.001

[a]Value from the last 50% dialog stressor in the positive condition (C4)
[b]Average value from the first 50% dialog stressor in both negative and positive condition (C1&C5)
[c]Value from the last 50% dialogue stressor in the negative condition (C8)
[d]The control conditions
[e]Mean and standard deviation of condition 1
[f]Mean and standard deviation of condition 2

The result of the overall analysis also showed that there was no significant overall main effect for the higher and lower social anxiety groups, ($F(3,20) = 2.87$, $p = 0.062$, $\eta^2 = 0.30$). However, the univariate test (see Table 3.2) showed a significant difference between the two groups on the SUD Score rating and audio length. As shown in Figure 3.5 and Figure 3.6, the higher social anxiety group rated the SUD score significantly higher and spoke significantly less than the lower social anxiety group. However, no significant difference between the higher and lower social anxiety groups was found regarding heart rate.

The overall doubly repeated-measure MANOVA found no significant overall two-way interaction effect between dialogue stressor and the two social anxiety groups on anxiety level, ($F(18,5) = 2.34$, $p = 0.176$, $\eta^2 = 0.89$). However, additional univariate analyses found a significant two-way interaction effect between dialogue stressor and the two social anxiety groups on SUD score rating and heart rate, as shown in Table 3.2. Furthermore, and as can be seen in Figure 3.5 and Figure 3.7, the difference between the higher and lower social anxiety groups in the SUD score rating and heart rate varied across conditions. For example, the higher social anxiety group reported a significantly higher ($t(22) = -3.35$, $p = 0.003$) SUD score rating in the maximum level of the dialogue stressor condition (100% negative dialogue style ratio) while no significant difference ($t(22) = -0.27$, $p = 0.79$) was found in the minimum level of the dialogue stressor condition (0% negative dialogue style ratio) between the two social anxiety groups. A similar pattern seems to appear in the heart rate at those two points in 3.7, although not significant this time (100% negative dialogue style ratio: ($t(22) = -1.78$, $p = 0.088$; 0% negative

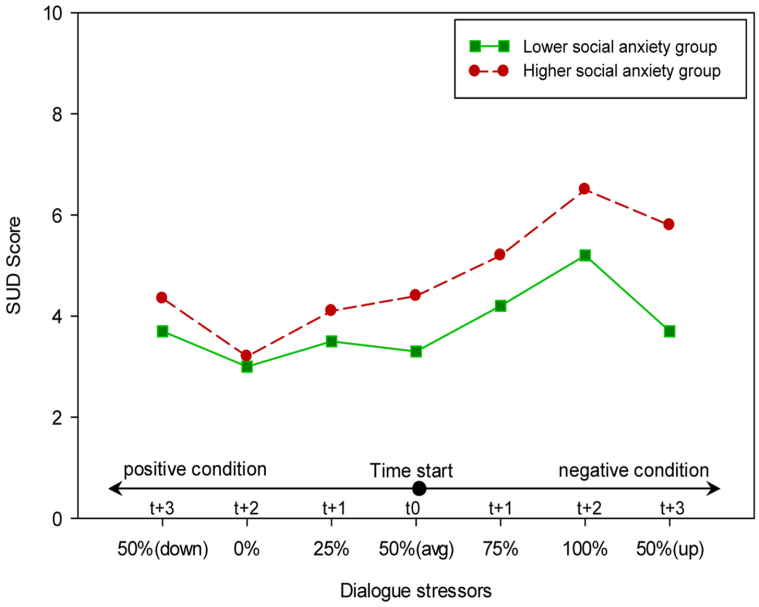

Figure 3.5: The effect of dialogues stressor on the participants' SUD score

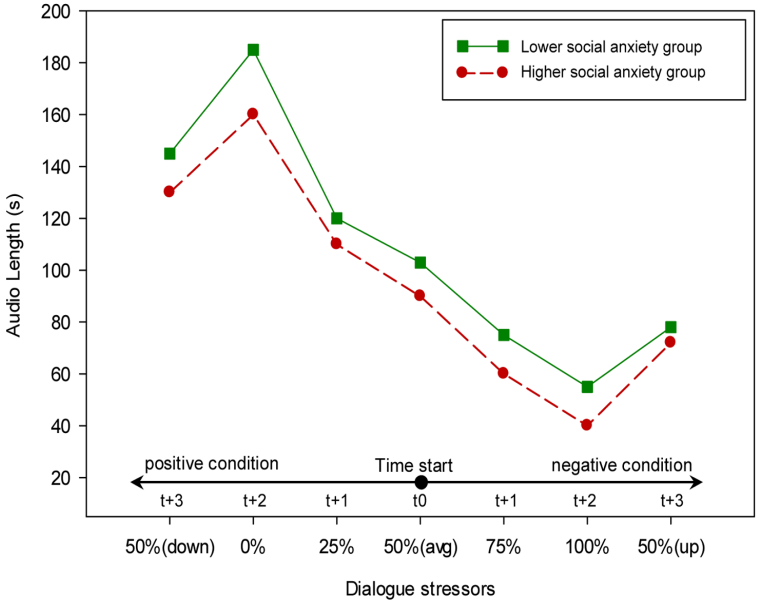

Figure 3.6: The effect of dialogues stressor on the participants' verbal communication (the length of the speak)

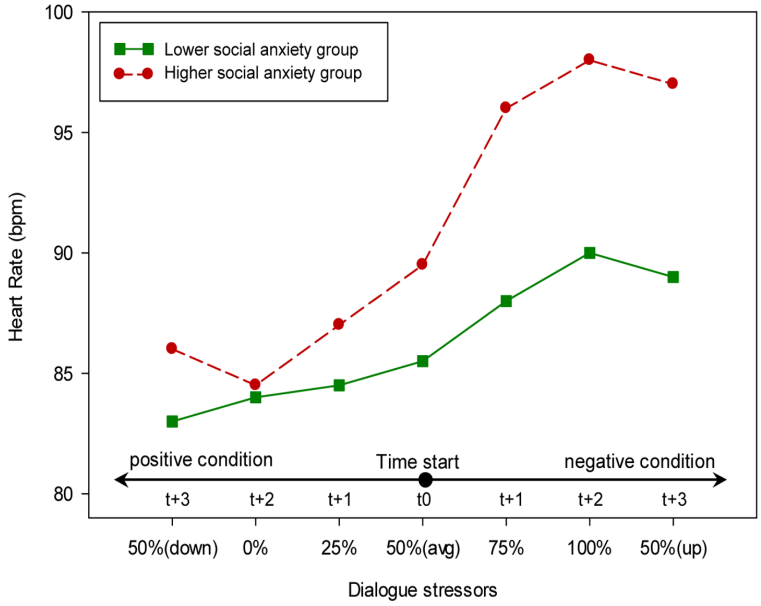

Figure 3.7: The effect of dialogues stressor on the participants' heart rate

dialogue style ratio: $t(5.53) = -0.28$, $p = 0.79$). Furthermore, no significant two-way interaction effect was found between different dialogue stressor and the two groups on the audio length, which seem to have a fixed difference between the two groups across the eight conditions.

As reported above, this experiment applied two control conditions (C4 and C8) (see also Figure 3.3). The C4 control condition aimed to bring the minimum dialog stressor levels (C3) back up to the starting conditions (C1), whilst the C8 control condition aimed to bring the maximum dialog stressor levels (C7) back down to the starting conditions (C5). Post-hoc analysis (see Table 3.3) of both the SUD score rating and verbal dialogue time (audio length) confirmed that both control conditions were able to increase and decrease (subjective) anxiety levels significantly from the minimum and maximum dialogue stressor level. Although this seems to support the hypothesis that the level of anxiety can be controlled into some specific level after it stretches to the maximum/minimum specific level (**H3**), no significant difference for the control conditions were found in heart rate of the participant.

PARTICIPANTS' EMOTION

For the participants' emotional experience during the exposure, univariate analyses on the SAM rating found significant effects for two dialogue stressor conditions (C1-C4 and C5-C8) on the valence, arousal and dominance affective dimensions (see Table 3.4). Compared to the negative dialogue condition, in the positive dialogue condition participants rated their emotional state as significantly more pleasant, more excited and more dominant (see Table 3.5).

Univariate analyses also found a significant two-way interaction effect for the anx-

Table 3.4: Results of univariate analyses with dialogue stressor as within-subjects factor and social anxiety group as between-subjects factor on the individuals' own valence, arousal and dominance state

Factor	Hyp. *df*	Error *df*	*F*	*p*	η^2
Valence					
Dialogue stressors	1	22	38.5	< 0.001	0.64
Social anxiety group (high and low)	1	22	0.13	0.724	0.01
Dialogue stressors x Social anxiety group	1	22	7.07	0.014	0.24
Arousal					
Dialogue stressor	1	22	19.98	< 0.001	0.48
Social anxiety group (high and low)	1	22	4.21	0.052	0.16
Dialogue stressors x Social anxiety group	1	22	9.09	0.006	0.29
Dominance					
Dialogue stressors	1	22	32.2	< 0.001	0.59
Social anxiety group (high and low)	1	22	8.75	0.007	0.29
Dialogue stressors x Social anxiety group	1	22	4.37	0.048	0.17

Table 3.5: Comparison between different conditions on the individuals' own valence, arousal and dominance state

Measurement	*M(SD)* Negative condition	*M(SD)* Positive condition	*t*	*df*	*p*
Valence	2.63 (0.88)	4.00 (0.78)	-5.01	23	< 0.001
Arousal	2.67 (0.76)	3.46 (0.78)	-2.94	23	0.007
Dominance	3.17 (0.92)	4.46 (0.59)	-4.99	23	< 0.001

iety groups and the dialogue stressor on the valence, arousal and dominance affective dimensions (see Table 3.4).

As depicted in Figure 3.8, on the arousal dimension, the high social anxiety group reported significantly more ($t(5.47) = -2.71$, $p = 0.039$) arousal than the low social anxiety group in the positive condition, while no significant difference ($t(22) = 1.25$, $p = 0.22$) was found in the negative condition. Furthermore, for the dominance affective dimension, the higher social anxiety group felt significantly less ($t(22) = 2.98$, $p = 0.007$) dominant than the lower social anxiety group in the negative condition, while this time no significant difference ($t(22) = -0.20$, $p = 0.846$) was found in the positive condition. Finally for the valence dimension, the higher social anxiety group rated valence not significantly higher ($t(22) = -1.91$, $p = 0.069$) than the lower social anxiety group in the positive condition, and no significant difference ($t(5.82) = 1.55$, $p = 0.173$) was found in the negative condition between the two groups. It seems therefore that the higher social anxiety group was more affected by dialogue stressor, while the lower social anxiety group was more stable across the positive and negative conditions.

PERCEPTION OF VIRTUAL HUMANS' EMOTION

Univariate analyses on the SAM rating of participants' perceptions of the virtual human's emotion (see Table 3.6) showed a significant effect for the dialogue stressor on three affective dimensions. Compared to the negative dialogue condition, the virtual human in the positive dialogue condition was perceived to be in state of significantly higher valence and arousal, but significantly lower dominance (see Table 3.7).

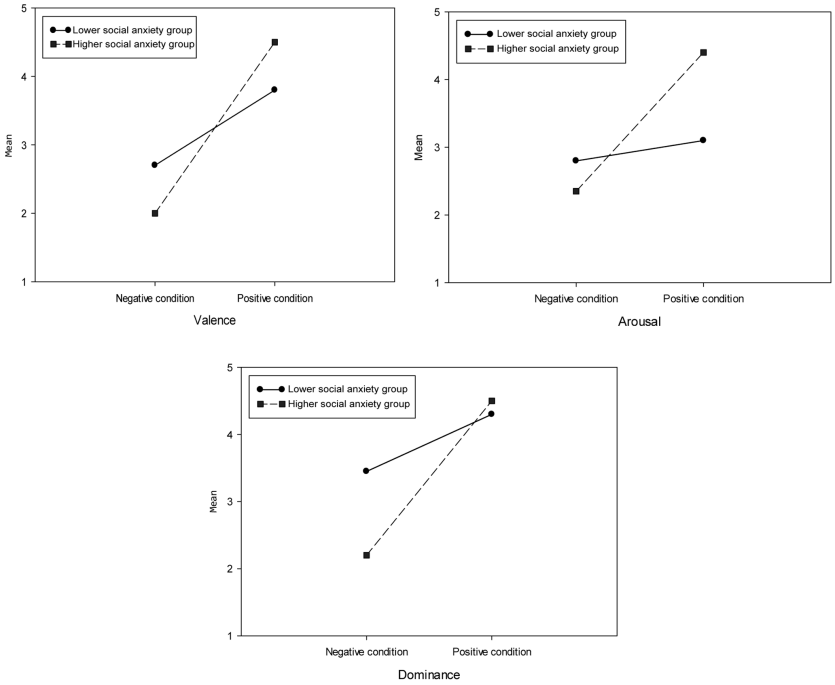

Figure 3.8: The effect of dialogue stressor on participants' own emotion in three affective dimensions

Table 3.6: Results of univariate analyses with dialogue stressor as within-subjects factor and social anxiety group as between-subjects factor on perceived valence, arousal and dominance of the virtual human

Factor	Hyp. *df*	Error *df*	*F*	*p*	η^2
Valence					
Dialogue stressors	1	22	166.91	< 0.001	0.88
Social anxiety group (high and low)	1	22	1.71	0.205	0.07
Dialogue stressors x Social anxiety group	1	22	14.07	0.001	0.39
Arousal					
Dialogue stressor	1	22	10.64	0.004	0.33
Social anxiety group (high and low)	1	22	4.97	0.036	0.18
Dialogue stressors x Social anxiety group	1	22	3.2	0.088	0.13
Dominance					
Dialogue stressors	1	22	25.27	< 0.001	0.54
Social anxiety group (high and low)	1	22	4.13	0.055	0.16
Dialogue stressors x Social anxiety group	1	22	0.52	0.48	0.23

Table 3.7: Comparison between different conditions on perceived valence, arousal and dominance of the virtual human

Measurement	*M(SD)* Negative condition	*M(SD)* Positive condition	*t*	*df*	*p*
Valence	1.71 (0.62)	3.92 (0.72)	-10.18	23	< 0.001
Arousal	3.04 (0.62)	3.67 (0.82)	-2.61	23	0.016
Dominance	4.1 (0.76)	3.08 (0.71)	5.45	23	< 0.001

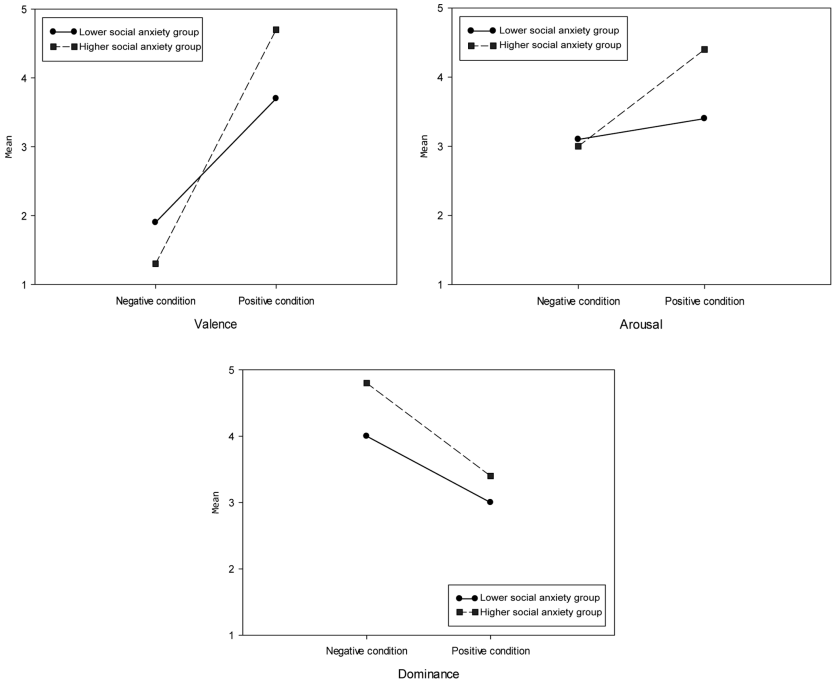

Figure 3.9: The effect of dialogue stressor on virtual human's emotion in three affective dimensions

A two-way effect for dialogue stressor and anxiety groups was only found on the valence ($F(1,22) = 14.07$, $p = 0.001$, $\eta^2 = 0.39$) affective dimension. As Figure 3.9 on valence rating shows, compared to the lower social anxiety group ($M = 3.67$, $SD = 0.59$), participants in the higher social anxiety group ($M = 4.67$, $SD = 0.52$) perceived the virtual human as exhibiting significantly more ($t(22) = -3.67$, $p = 0.001$) valence. No significant difference ($t(22) = 1.78$, $p = 0.089$) however was found in the negative condition between the two groups.

DIALOG EXPERIENCE AND INTERVIEW ATTITUDE

Analysis of the total DEQ score and IAQ score showed that compared to the negative dialogue condition (DEQ: $M = 32.84$, $SD = 1.00$; IAQ: $M = 20.38$, $SD = 4.2$), in the positive condition (DEQ: $M = 38.32$, $SD = 1.24$; IAQ: $M = 30.25$, $SD = 3.21$) participants rated their dialogue experience more positively ($F(1,22) = 252.56$, $p < 0.001$) and they also had a significantly ($F(1,22) = 103.6$, $p < 0.001$) more positive attitude toward the interview. On average the higher social anxiety group ($M = 23.92$, $SD = 0.92$) rated their attitude significant lower ($F(1,22) = 22.38$, $p < 0.001$) than participants in the lower social anxiety group ($M = 25.78$, $SD = 0.81$). The analysis of the IAQ score also revealed a significant two-way interaction effect ($F(1,22) = 19.82$, $p < 0.001$) for the anxiety group and dialogue stressor. As Figure 3.10 shows, in the negative dialogue condition, the attitude of the higher social anxiety group was significantly lower ($t(5.26) = 3.55$, $p = 0.015$) than the lower social anxiety group, while in the positive dialogue condition there was no significant difference ($t(5.57) = -1.85$, $p = 0.118$) between both groups. Moreover, the lower social anxiety

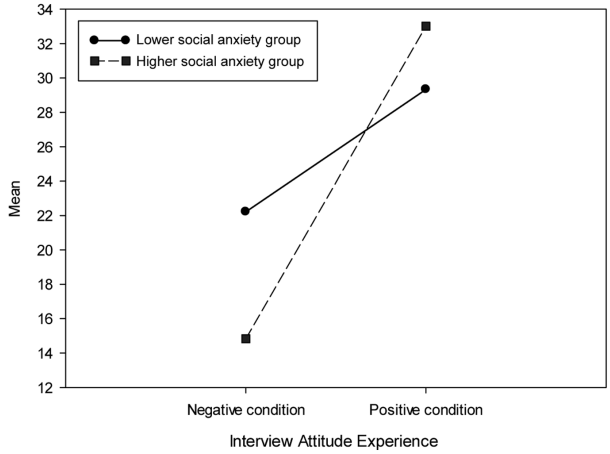

Figure 3.10: The effect of dialogue stressor on participant's interview attitude experience

group rated their attitude significantly more positively ($t(17) = -10.16$, $p < 0.001$) in the positive dialogue condition compared to the negative dialogue condition. Likewise, the higher social anxiety group rated their attitude significantly more positively ($t(5) = -4.64$, $p = 0.006$) in the positive dialogue condition compared to the negative dialogue condition.

3.5. DISCUSSION AND CONCLUSION

THE results of the first study support the hypothesis that various social scenes in virtual reality can have a different effect on the individuals' anxiety levels. As the social situation changed from a neutral VR world to a blind date situation or a job interview situation, the individuals' anxiety level significantly increased, which suggests that various VR situations can evoke different levels of anxiety. Furthermore, in the second study, the manipulation of a dialogue feedback stressor in the dialogue-based VRET system for social anxiety had a significant effect on individuals' level of anxiety, their attitude, their dialogue experiences, their speech behaviour, their own emotions, and how they perceived the emotion of the virtual human. These results suggest that within a dialogue the ratio of positive and negative responses can be applied as an effective anxiety stressor. Of importance are also the results found in the control condition (C4 and C8) where polarity of ratio was again reversed. This showed that levels of anxiety could be influenced and controlled dynamically; i.e. anxiety could not only be increased or decreased to a maximum or a minimum level, but also reversed halfway. This is important as it would give therapists extensive freedom to stabilize anxiety of a person on a desired level. Finally, participants with more social anxiety were more affected by the dialogue stressor than other participants. Our results show that the individuals' degree of social anxiety is related to the level of anxiety and avoidance behaviour, i.e. less speaking during exposure. This was also related to how they perceived the emotion of the virtual human and reported on their own emotion.

Our findings have implications with regard to virtual reality exposure therapy for anx-

iety disorders in general and social anxiety disorder in particular. First and foremost, our results indicate that virtual social interactions can be effectively used in virtual reality exposure therapy to provoke social anxiety. Additionally, our results demonstrate that social dialogues in virtual environments can be effectively manipulated for therapeutic purposes. Accordingly, our findings are promising with regard to the use of virtual reality exposure therapy for different psychological complaints that might involve social interactions between patients and virtual human. For example, virtual social environments might be effectively used to train social skills for individuals with other complaints than social phobia. Furthermore, this study builds on previous work that demonstrated that specific social scenes [29,30], avatars' body posture [52] and avatar's facial expression [53] can elicit anxiety. This study adds to this body of work by introducing the dialogue stressor ratio that can be manipulated *on-the-fly* within the scene. Hence, it can give the therapist the flexibility to control social stressors during exposure.

Despite the promising results, the studies also have limitations that should be considered. First, the dialogue system was designed as such that the computer took the lead in the conversation in order to limit the number of potential answers by the participants. However, some social anxiety disorder patients might specifically fear a situation where they have to start and lead a conversation. They therefore might benefit from being exposed to such situations. Second, the social setting focused on two scenes only: blind date and job interview, where social phobia patients normally fear a range of social situations. Still, the findings might generalise to these other situations if they incorporate a question and answer style conversation. Third, this study did not include individuals diagnosed with social anxiety disorder. If anxiety is considered a continuous scale, the difference found in this study between lower and higher anxiety individuals might also be generalised to individuals higher up the social anxiety scale. Fourth, in the second study, the post self-reported experience of individuals' own emotion showed a significant reduction in the arousal, valence, and dominance dimensions in the negative compared to the positive dialogue condition. This might suggest that participants experienced the emotion of hurt alongside or instead of anxiety following exposure. However, the self-reported subjective discomfort and heart rate data collected during exposure rather indicated an anxiety response during exposure. Future research should consider using multi-dimensional emotion measures [48,54] during virtual reality exposure.

The main scientific contribution of the study lies in the validation of dialogue stressor as a stimulus that can induce anxiety. Besides psychotherapy, this could also benefit other application domains such as psychological stress testing, e.g. Trier Social Stress Test (TSST) training [55-57], job interview or negotiation simulations [58], or gaming. As in all these domains individuals could benefit from conversation that could elicit stress.

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4

COMPUTER-BASED FEAR REGULATION DURING VIRTUAL REALITY EXPOSURE FOR SOCIAL ANXIETY

Although several studies have demonstrated the efficacy of virtual reality exposure therapy, current virtual reality systems require therapists to manually adjust anxiety stressors for the patient to elicit the required anxiety response during exposure. Introducing a feedback-loop mechanism to measure anxiety and adjust anxiety stressors automatically enables a more autonomously delivery of anxiety exposure. To study effectiveness of such an automatic regulation mechanism, an experiment was conducted to examine the system's ability of keeping individuals' anxiety on a fixed target level. A group of 24 healthy participants were exposed to both (1) a static condition, where anxiety stressors remained fixed during the session, and to (2) a dynamic condition, where anxiety stressors were automatically adjusted in correspondence with the individual's self-reported anxiety and heart rate. Prior to virtual reality exposure, a personalised anxiety measure was automatically established for each participant. Here, imaginary exposure was used to measure anxiety response in a lower and a higher anxiety situation. The results revealed that a personalized anxiety measure can be established automatically. Furthermore, while anxiety dropped in the static condition, anxiety in the dynamic condition remained centered around the target anxiety level (-4.82%) over time. Our findings have first and foremost implications for the use of virtual reality programs that target social anxiety. Yet, we anticipate that the- proposed feedback loop mechanism can be beneficial when applying virtual reality to address emotions in general.

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Keywords: *Virtual reality exposure therapy, feedback-loop, dialogue stressor, social anxiety, emotion regulation, anxiety measurement.*

4.1. INTRODUCTION

SEVERAL studies have reported on the efficacy of virtual reality exposure therapy (VR ET) for treating social anxiety disorder [1-4]. In VRET, patients are exposed to virtual reality environments that resemble feared real life situations. As in exposure in vivo, patients undergoing VRET need to experience a certain amount of anxiety before emotional processing can take place. Currently therapists externally manipulate anxiety provoking stimuli in the virtual world for therapeutic purposes. For example, in the treatment of social anxiety disorder the therapist controls the amount of positive or negative comments made by a virtual conversation character [5]. Automating this external regulation mechanism would remove the need for direct therapist intervention during exposure, reducing therapist workload and opening ways for more autonomously delivery of exposure, including distance therapy [6,7]. This paper focuses on the development of such an automated mechanism and an empirical evaluation of its ability to regulate anxiety.

Besides its efficacy, VRET is also more readily accepted by patients [8] compared to exposure in vivo. Contrary to in vivo exposure, VRET makes the control of exposure elements more manageable and treatment might be more cost effective since the patient is exposed in a virtual environment (VE) where the parameters of anxiety evoking stimuli can be easily changed and manipulated. Several anxiety disorders have been explored for their ability of using VRET technology such as fear of flying [9], acrophobia [10], arachnophobia [11], claustrophobia [12], Posttraumatic Stress Disorder (PTSD) [13] and social phobia [14]. VRET systems used for social phobia often focus on recreating a social scene setting, such as a public speaking scenario, clothing shop, public transport, and restaurant. These setups allow patients to be exposed to different social situations. Besides the feared social scenario itself, therapists can also manipulate the anxiety stressor within a particular scenario. For example, they can modify the dialogue style to be more or less friendly, the eye gesture and the body posture [5].

For exposure treatment to work, patients need to experience a certain amount of anxiety [15]. Some treatment manuals [16] suggest as a general rule to target an anxiety level between 5 to 7 on a scale from 0 (no anxiety) to 10 (extreme anxiety). The process of obtaining such anxiety levels cannot simply be modelled as a fixed stimuli-response format. Instead, stimuli responses vary between patients as well as over time, and therefore they can better be modelled as a negative feedback loop. In this case, stimuli need continuous adjustment based on deviations observed between measured and desired anxiety levels. For this to work, continuous anxiety measurement is essential. Although automatic self-reported anxiety measures can be applied during social interaction with virtual humans [17], other measurement sources are required as self-report anxiety measures might not always be reliable. For instance, patients sometime report social desirable response [18]. Therefore, multi-modal measuring, whereby self-reported data is combined with for example a physiological measurement [19], is desirable. To be effective, however, such measurement requires calibration to adjust for individual differences in reporting anxiety and in the autonomic nervous system response towards perceived threats [20].

In this paper, we present the design and evaluation of an automatic multi-modal feedback-loop mechanism, which includes an automatic procedure to calibrate a multi-

modal anxiety measure. By implementing the mechanism in a VRET system for social anxiety, we empirically evaluate its ability to maintain individual's anxiety centred on a predefined target level.

4.2. RELATED WORK

FOR many years, in vivo exposure is considered the gold standard treatment of anxiety disorders, including social anxiety disorder. Here, patients are gradually exposed to situations they fear until their fear is manageable. Although effective, in vivo exposure has several drawbacks. For example, it might be difficult for the therapist to organize and control situations that seem relevant in treating specific complaints [21]. Exposure in virtual reality can overcome these limitations. Most studies on VRET for social anxiety disorder have focused on the fear of public speaking [4,22,3]. Still other social scenarios have also been developed such as job interviews, social interaction in a shopping mall, restaurant, public spot, metro, and train station, and airport [5,23,24,14]. The main objective in our project has been to provide therapists with a variety of dynamic social stressors that they can modify in the scenario and use to regulate patient anxiety externally.

Emotion can be expressed through various channels, such as physiological responses, speech and gestures [25]; and its state can be described in a multi-dimentional model, organized along axis such as valence, arousal, and dominance [26]. In this three dimensional space fear and anxiety would be positioned in the corner of high arousal, negative valence, low dominance. Often a distinction is made between fear and anxiety [27]. Fear is a response to a real or perceived threat and associated with strong psychological arousal for a possible fight or flight response; whereas anxiety is an anticipatory reaction to a future threat and is associated with muscle tension, highten level of vigilance, and also avoidant behaviours [28]. In other words, anxiety is prestimuli, and fear is poststimuli [27]. Fear is there-fore seen as a cognitive appraisal. Still, fear could also trigger anxiety, which is a more enduring state [29]. The difference between adaptive and maladaptive fear and anxiety is that they are more recurrent, persistend, and their intensity is unreasonable [27].

The notion of computer-based emotion modification using physiology in a feedback-loop is not new [30]. Yet, often it has been implemented as a positive (Figure 4.1-A) instead of a negative feedback loop system (Figure 4.1-B). Whereas a negative-feedback loop systems [31] aims at maintaining emotion at a certain target level, a positive-feedback loop system pushes the emotional state in a specific direction without a specific target level. Next, emotion regulation is internal and thus it is up to the individual to modify their emotion to move away from an undesirable state. Applications that provide biofeedback are clear examples of this approach. For example, Healey and Picard [26] use various physiological data (electrocardiogram, electromyo-gram, skin conductance and respiration) incorporated in a feedback loop driving simulator to determined driver's stress level. Cosic et al. [32] developed adaptive virtual reality stimulation for the prevention of PTSD utilizing physiological feedback signals to estimate person's emotional state. In affective gaming, the game's responses to players' emotional state aim at motivating the player to alter it. Examples of these games are Konami dating game [33], Tetris 64 [34], Mindlink [35], and Nevermind [36]. These games use a variety of

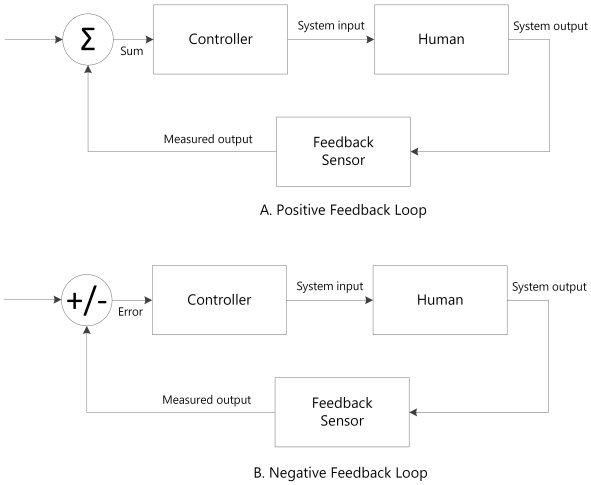

Figure 4.1: Positive (A) and negative (B) feedback loop basic diagram block

biosensors such as heart rate, skin conductance, and pulse oximeter, to measure and provide players with feedback about their emotional state. Besides entertainment products, computer-based emotion modification also been used for training. For example, Bouchard et al. [37] used a first-person shooter with bio-feedback to train the soldier to lower their stress response when confronted with stressful scenario. Furthermore, such positive feedback systems with bio-feedback have also been studied for mental disorders such as schizophrenia, depression, anxiety disorders, insomnia, alcohol and drug dependence, and tardive dyskinesia [38,39].

A main challenge for moving from a positive towards a negative feedback loop system is to establish an anxiety scale, on which therapists can set a target level and which can be aligned with automatically collected emotion indicators such as heart rate or subjective anxiety measures. Quantifying or categorizing emotion measuring data is however not a trivial task [40]. Sever-al studies [41-43] reported difficulties to classify the emotion in automatic fashion because of issues, such as: the lack of a “ground truth” to calibrate or train a system [41], and individual difference towards standardized emotional stimuli material used for validating measures [43,42]. Despite these problems, combining several emotion measures has been shown to improve the overall accuracy of automated emotion measurement. For example, Drachen et al. [44] confirmed the ability to produce a realible measure of affective player experience, emotions, and cognition by combining self-reported data with heart rate and electrodermal activity as sensory input obtained during game. Furthermore, Lefter et al. [45] used combined human speech and gesture modalities as realible input measurements variables in automatic surveillance stress recognition system. Moreover, Yannakakis et al. [46] combined both children’s heart rate, skin conductance signal and their expressed preference of “fun” as a realible engagement measurement in interactive gameplay environment.

To establish a negative-feedback loop system for external anxiety regulation, a system also requires scalable stimuli. Contra to the classical example of a room temperature regulation system that works by turning the heating system full on or off, patients should

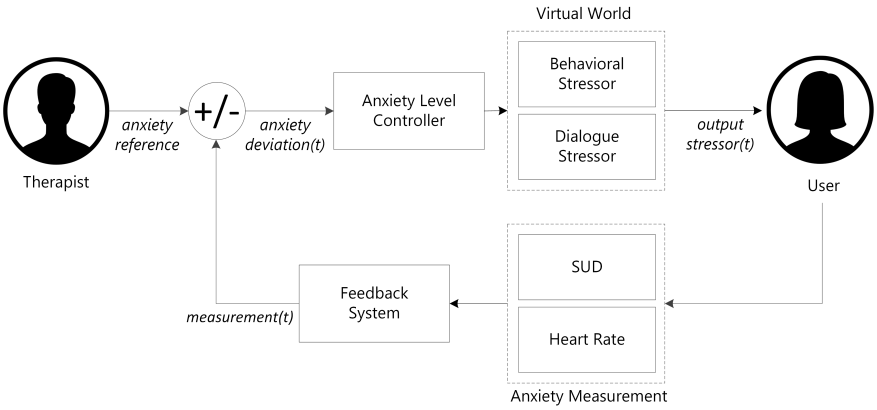

Figure 4.2: Automatic multi-modal anxiety feedback-loop block diagram

not be exposed to too frightening stimuli at once, i.e. flooding [47]. Instead, exposure should be done gradually, which requires therefore scalability. Fortunately, some studies have already shown that this is in principle possible for VRET for social phobia. For example, several studies [24,48] showed that varying the distance towards virtual human led to variation in anxiety response. Also Hartanto et al. [5] showed that in the setting of a job interview, the number of positive or negative formulated questions and response to answer of individuals had a strong correlation with measured anxiety.

4.3. SYSTEM DESIGN

As Figure 4.2 shows, during the experiment, the anxiety regulation mechanism was implemented as a negative feedback loop in a VRET system. It monitored the patient's anxiety and considered its deviation from a reference value set by a therapist. The existence, direction and the magnitude of any deviation led the system to adjust the anxiety stimuli material. In other words, if the anxiety level measurement was below the target level, the phobic stressors were proportionally increased. If the deviation was negative, the phobic stressors were proportionally decreased. For this, the system included three key elements: (1) the multi-modal anxiety measurement, (2) the feedback loop mechanism, and (3) the stressors element. By reading participant's anxiety level (i.e., by combining their subjective score and their heart rate), the system was able to compare this with the reference value anxiety and adjust the stressor.

To determine individual levels of anxiety, the VRET system collected both subjective data by means of the Subjective Unit of Discomfort (SUD) scale using speech technology [17], and physiological measurement data in the form of heart rate (bpm unit) [49]. Previous studies [5,1,24] that measured anxiety during a dialogue with a virtual human reported both these measures as realible. These measures were combined into a single unit anxiety measure.

As mentioned before, to be able for a therapist to set a reference value, the anxiety measure needed to be aligned with a standard scale. To cope with the individual variation, a personalized anxiety measure was developed for each user. To create this measure

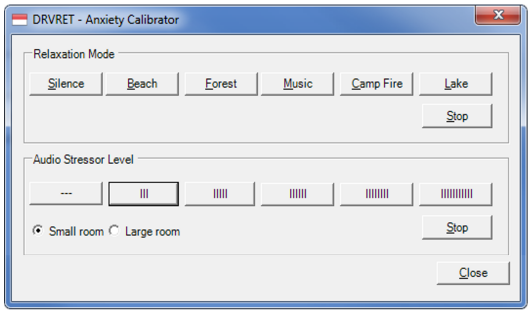

Figure 4.3: Anxiety calibrator used in the experiment

a pre-session calibration procedure was used. Here, we calibrated the anxiety measurement algorithm using imaginary exposure [50,47,51] to establish the model parameters and input values. To do this, users were exposed to a relaxing situation as well as a high anxiety situation, which allowed for the determination of a lower-bound, defined as a value zero % on the anxiety scale (y = 0), and an upper-bound level of anxiety scale, defined as 100% on the anxiety scale (y = 100). To support them experiencing a low level of anxiety (relaxation), the system provided a wide variety of relaxation audio clips (e.g., beach, lake, jungle, and campfire). Using these sound clips and their imagination, the system instructed users to relax for 4 minutes while the system recorded their heart rate and SUD score every minute.

Thereafter, the system asked users to imagine giving a presentation and provided them again with sound clips. These sound clips were recordings of audiences ranging from a quiet audience, to an audience making a bit of noise, and up to an audience that was loudly boo-ing (Figure 4.3). In addition, the user could also select sound clips recorded in a small or large room to simulate different number of crowd. The system instructed the users to expose themselves to the most anxiety-provoking situation that they considered still tolerable. Again, the system collected their anxiety data for 4 minutes period. This calibration session was performed without wearing a Head Mounted Display (HMD) device, as previous work shows that simply wearing a HMD and being immersed in a virtual world does not have to lead to increased levels of anxiety [52] and therefore was not regarded as an additional stressor of a VRET system needed to be considered in the calabration procedure.

Based on both SUD and heart rate measurement, the system created an individual linear regression model at run-time. The linear regression was chosen over more advanced techniques such as multi-modal feature level fusion [53], multiset canonical correlation analysis [54] or parallel factor analysis [55], because it is relatively easy to implement [56] and as previous work [5] showed linear functions are very effective in describing anxiety variation. It formulated a single anxiety measurement on which the anxiety level controller acted using the following set of equations:

$$\hat{\gamma}_i = \beta_0 + \beta_1 \times HeartRate_i + \beta_2 \times SUD_i \tag{4.1}$$

$$\hat{\gamma}_i = \beta_0 + \beta_2 \times SUD_i \tag{4.2}$$

$$\hat{\gamma}_i = \beta_0 + \beta_1 \times HeartRate_i \tag{4.3}$$

Otherwise,

$$\hat{\gamma}_i = -170.44 + \beta_0 + \beta_1 \times 1.033 + \beta_2 \times 32.65 \tag{4.4}$$

Where $\hat{\gamma}_i$ represent person's level of anxiety, β_0, β_1 and β_2 were the offset and the regression coefficients for predictor variables SUD and heart rate. Equation 4.1 shows the most ideal rule that could be used as enough variation on both SUD score and heart rate was measured during the calibration procedure. If that was not the case, the other rules were used as a fall back scenario. Equation 4.2 was used if only the SUD score showed enough variation, i.e. was larger than 0. Equation 4.3 was used if only the heart rate data showed enough variation, i.e. was larger than 4 beats per minute (bpm). Finally, Equation 4.4 was used if both SUD and heart rated showed insufficient variation. Here the system relied on the data collected in a previous experiment [5]. In other words, the measure would not be personalized, but would use mean parameter estimations obtained from another group of individuals.

During the session this measure was used to control stimuli material, i.e. output stressor. For this, the following simplified feedback-loop equations were used:

$$measurement(t) = measurement(t-1) + K_f \times outputstressor(t) \tag{4.5}$$

$$outputstressor(t) = outputstressor(t-1) + K_b \times anxietydeviation(t) \tag{4.6}$$

$$anxietydeviation(t) = anxietyreference - measurement(t) \tag{4.7}$$

Where output *stressor(t)* was the virtual world's anxiety evoking stimuli at time *t*, *measurement(t)* was the user's measured anxiety level at time *t*, *anxiety reference* was the desired anxiety level set by the therapist, and *anxiety deviation(t)* was the deviation of the measured anxiety from *anxiety reference* set by the therapist. Equation 4.5 formulates that the variation in users' anxiety at time t is assumed to be proportional to the variation in the *output stressor* at that point in time. K_f is the forward proportionality constant. It represents the speed in which human's reaction to *output stressor*. It captures the effectiveness of the particular feedback-loop mechanism while regulating the participant's anxiety level. Equation 4.6 defines the anxiety level for the controller module. In the proposed feedback-loop system this was a simple proportional controller model, derived from classic PID (proportional-integral-derivative) control theory [57]. The larger the *anxiety deviation(t)*, the larger the changes in the *output stressor*, with the backward proportionality constant K_b controlling magnitude and speed by which the *output stressor* would be adjusted to accommodate individual's anxiety reactions. While a large K_b value would make the system respond quickly to *anxiety deviations*, a small K_b value would protect the system against instability and oscillation. Finally, Equation 4.7

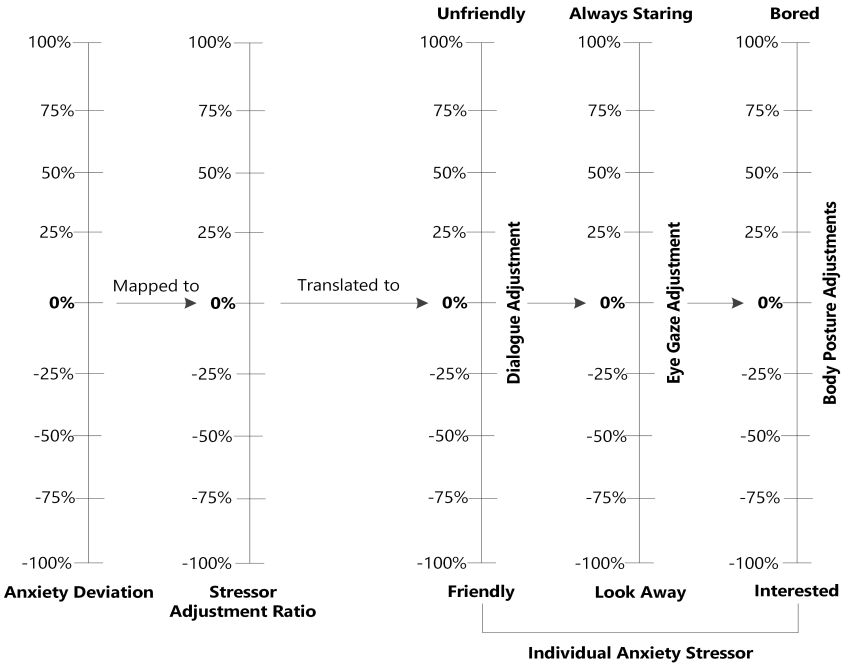

Figure 4.4: Anxiety controller module mapping algorithm

defines *anxiety deviation* as the difference between *measured anxiety* and *anxiety reference*. For standardization, the *anxiety deviation* was expressed in percentage deviation from the *anxiety reference*, defined as:

$$anxietydeviation(\%)(t) = \frac{anxietyreference - measurement(t)}{anxietyreference} \tag{4.8}$$

Although Equation 4.6 refers to the *output stressor* as a single stimuli element, it was in fact a combination of three stressors: dialogue stressor, eye gaze stressor, and body posture stressor. Figure 4.4 shows that the *anxiety deviation* was mapped to the overall stressor adjustment ($K_b \times$ *anxiety deviation(t)*), which was again mapped to the individual anxiety stressors. The following equation defines how each individual stressor was mapped to *anxiety deviation%(t)*, which limited to 0% lower bound and 100% upper bound:

$$VRstressor\%(t) = VRstressor\%(t-1) + stressoradjustment\%(t), [0,100) \tag{4.9}$$

As mentioned above, three different anxiety stressors were implemented in the VRET system. The first one was the dialogue stressor, which related to friendliness or unfriendliness of the conversations. The stressor's level was expressed as a ratio between positive and negative dialogue units in a dialogue. Here, a dialogue unit was defined as:

Figure 4.5: (**Left**) Physical equipment participant used during the experiment: head mounted display (HMD) with head tracker, heart rate monitoring devices; Mobi 8 (finger clips), Zephyr HXM (chest band) and a microphone. (**Right**) The female and male interviewers with different body postures and eye gaze seen by the participant

[**virtual human's question**]→[**user's answer**]→[**virtual human's response on user's answer**]. A positive dialogue unit mean that the question and response of virtual human was friendly, affirmative or enthusiastic, such as "*What is the biggest mistake that you have made?*" and followed by the virtual human response toward user's answer "*Interesting! So you have learned a lot starting from that moment then.*". On the other hand, a negative dialogue unit meant a question or respond with a unfriendly, unenthusiastic or criticizing tone, such as "*I can see that you've made lot of mistakes in the past, can you tell me the biggest one?*" and followed by the virtual human's response "*Stupid one! Here we don't tolerate this kind of mistakes!*". Setting the stressor ratio for example to 70% would mean there was a 70% chance that system would select a negative dialogue unit and 30% chance it would select a positive dialogue unit from the set of possible dialogue units. Previous research demonstrated that modification of dialogue ratio was strongly associate with variations in people's self-reported anxiety, their heart rate, and length of their answers [5].

The second anxiety stressor was the eye gaze of the virtual human (Figure 4.5). As reported elsewhere [58,59], the degree of (intense) direct eye gaze is associated with eliciting anxiety in people. Therefore, the VRET system varied the time the virtual human would gaze directly at a user during a dialogue unit. As not looking at a human speaker can also evoke anxiety [60], the virtual human would at least look 30% of time towards users. The eye gaze stressor, therefore, only related to the remaining 70% of the time. For example, if the eye gaze was set to 60%, the virtual human would for $(.3 + .7 \times .6)$ 72% of remaining time fix its eye gaze on the user and for 28% look away from the user.

The third anxiety stressor was the body posture of the virtual human [61], specifically the degree of interest or boredom it exhibited. This is important, as people are able to

notice this in the body posture of a virtual human. Specially the degree of attentiveness is a very recognizable feature in the body posture of virtual humans [62]. In the VRET system setting the body posture for example to 40% meant that there was a 40% chance the system would select a body posture animation displaying boredom and 60% it would select an animation displaying interested attitude.

4.4. HYPOTHESES

TWO hypotheses were formulated to test the usefulness of the proposed automatic anxiety regulator system. The first hypothesis addressed the calibration procedure's ability to collect a person's anxiety response in a lower and a higher anxiety situation. Finding no support for this hypothesis would render the procedure unusable and thereby failing to create a personalized anxiety measure. The hypothesis was formulated as:

> **Hypothesis 1 (H1)**: *Individual's anxiety is lower in the relaxation condition than in the anxiety condition of the calibration procedure.*

The second hypothesis addressed the system's ability to regulate anxiety. To test its effectiveness, it was compared to a situation with no such system in place, i.e., a situation where no adjustment was made to anxiety stimuli. As habituation to anxiety provoking situations sets in over time, people's anxiety was expected to drop [4]. Therefore to test the system, this natural decline in anxiety was contrasted with a situation where the system would try to maintain anxiety level on a pre-set level. Although keeping a phobic patient for over a longer time period on a heightened level of anxiety might not have a direct therapeutic application, it would demonstrate the system's ability to regulate anxiety. This for example could be therapeutically beneficial if a therapist first wants a patient to experience a certain level of anxiety, after which anxiety stimuli material remain fixed and the patient can experience a reduction of his/her anxiety. Therefore, the second hypothesis was formulated as:

> **Hypothesis 2 (H2)**: *While individual's anxiety level drops over time during an exposure session without automatic anxiety regulation, with such a mechanism the anxiety level remains centred around a pre-set anxiety reference value.*

4.5. METHOD

4.5.1. ETHICS STATEMENT

THIS study was conducted at a university laboratory and was approved by university human research ethics committee. As normal proceeding, written informed consent was obtained from all participants prior to the experiment. As a token of their participation in the experiment, all participants received snacks (cookies or chocolate bar) and drinks (coffee, tea or warm chocolate) after the experiment had finished.

4.5.2. EXPERIMENT DESIGN

To study the two main hypotheses, a within-subject experiment was conducted. Each participant was exposed to two different system response conditions: static, i.e. no anx-

iety regulation, and dynamic system response conditions, i.e. with automatic anxiety regulation. The order of those conditions was counter-balanced, as well as the two virtual job interviewers to control for possible learning effect. In the static system response condition, participants were exposed to a so-called static VR stressor, which meant that all the vr stressors % was fix to 70% and never changed. On the other hand, in the dynamic system response condition, participants were exposed to a dynamic vr stressor %, which meant that stressors dynamically changed depending on the participants' anxiety level.

4.5.3. PARTICIPANT

Twenty-four participants (15 females and 9 males) were recruited during the study. Seven participants were recruited from Erasmus University Rotterdam and the other from Delft University of Technology. All participants were master and PhD students with their age ranging from 24 to 34 years old (M = 27.54; SD = 2.45). All participants reported to have seen 3D movies but only four of them had been immersed into a virtual reality environment before. Furthermore, all participants were naïve to the hypotheses of the study.

4.5.4. MEASUREMENTS

OUTCOME MEASURE

SUD Score

The participants' level of anxiety during exposure in the virtual reality were measured using Subjective Unit of Discomfort (SUD) scale developed by Wolpe [63]. The SUD scale ranges from zero, which means no anxiety at all, until 10, which means the highest anxiety level that the person can imagine. The response was automatically collected using speech recognition [17].

Heart Rate and Heart Rate Variability (RMSSD)

To observe the participants' physiological activity (i.e., heart rate) during the exposure in virtual reality, a Zephyr HXM monitoring device in the form of chest-band and Mobi 8 device from TMSI with Xpod Oximeter was used (Figure 4.5). The Mobi 8 was only used as system backup measurement for Zephyr device recording. To measure the autonomic activity, especially the autonomic nervous system, the variation of interval between heart-beats during the exposure, i.e. the participants' heart rate variability (HRV) was recorded and calculated. For this, time domain measurement method RMSSD (Root Mean Square of the Successive Differences) [64] was used, calculated in ms unit.

Multimodal Anxiety Scale

Participants' overall anxiety level was measured by an internal anxiety scale used by the system, which was based on SUD score and heart rate (Equation 4.1 - 4.3).

Verbal Communication Effect (Behavioural Changes)

Besides the physiological activities, the (speech) behavioural activity of the participants was also observed. As documented in previous studies [4,65], speech behavioural changes, for example the length of speech, are an indicator of the level of distress or avoidance behaviour toward anxiety provoking situation. In this study, to record the total length

of speech from each participant during the interview in the virtual reality environment an auto detect speech algorithm [17] was used. All speeches from participants were recorded and measured in the unit of seconds (s).

PROCESS MEASURE

Interview Attitude Questionnaire (IAQ)
The IAQ was used to measure participants' experience and attitude toward the job interview [5]. The IAQ consists of six items rated on a seven-point scale. Those item are: (1) pleasant – unpleasant (reversed), (2) not relaxed – relaxed, (3) aggressive – not aggressive, (4) uncomfortable – comfortable, (5) polite – impolite (reversed), and (6) energizing – exhausting (reversed). The total score was calculated by accumulate all the individual items.

Dialogue Experience Questionnaire (DEQ)
Since the experiment involved dialogues between a virtual character and the participants, it was important to measure participants' perception of dialogue quality, such as the dialogue flow, the speed of the dialogue, and the reality of the dialogue content. To measure this perception of the dialogue quality, the DEQ was used. The DEQ was developed by ter Heijden et al. [58] and consists of 32 items rated on a seven-point scale ranging from 1 (strongly disagree) until 7 (strongly agree).

Participant's Own Emotion and Perception of Virtual Human
During exposure in virtual reality, participants' own emotion and their perception of the virtual interviewer's emotion were measured using the Self-Assessment Manikin (SAM) questionnaire. SAM is a widely used questionnaire to measure a person' affective reaction in the amount of pleasure, arousal, and dominance toward various stimuli [66].

DESCRIPTIVE MEASURE

Social Interaction Anxiety Scale (SIAS)
SIAS questionnaire [67] was used to divide participants into two groups of higher or lower social anxiety and as well to evaluate their social interactional activity. The SIAS questionnaire contain 20 items and each item related to discomfort feeling in a social scenarios, for example "I feel I'll say something embarrassing when talking" or "I become tense if I have to talk about myself or my feeling". All items are rated on a five-point scale from 0 to 4. 0 means "not at all characteristic or true for me" and 4 means "extremely characteristic or true for me".

Presence
The Igroup Presence Questionnaire (IPQ) developed by Schubert et al. [68] was used to measure the sense of being presence in the virtual reality,. This questionnaire has 14 items rated on a seven-point scale to measure three dimensions: involvement, spatial presence and experienced realism. Furthermore, the IPQ also has one item that measures the general feeling of being in the virtual reality.

Table 4.1: Comparison between relaxing and anxious condition during calibration phase

Time-slot (minutes)	Relax condition *M*(*SD*)	Anxious condition *M*(*SD*)	*t*(23)	*p*	*d*
SUD score (0-10)					
0 – 1	1.58 (0.50)	2.33 (0.64)	-4.98	<0.001	-1.02
1 – 2	0.88 (0.61)	3.25 (0.74)	-13.29	<0.001	-2.71
2 – 3	0.42 (0.50)	4.17 (0.76)	-19.46	<0.001	-3.97
3 – 4	0.21 (0.41)	5.17 (0.96)	-30.12	<0.001	-6.15
Heart rate (bpm)					
0 – 1	65.48 (2.44)	88.92 (2.66)	-30.51	<0.001	-6.23
1 – 2	64.40 (1.98)	89.45 (3.12)	-35.01	<0.001	-7.15
2 – 3	62.00 (1.72)	90.48 (3.37)	-37.69	<0.001	-7.69
3 – 4	60.42 (1.37)	92.05 (3.09)	-46.03	<0.001	-9.39

4.5.5. PROCEDURE AND APPARATUS

Prior to the experiment, all participants received a short introduction about the overall aim of the study and signed a consent form. After that, they filled in a basic information questionnaire (i.e., age, education, occupation, etc.) and SIAS questionnaire.

The main part of the experiment consisted of three different sessions: the calibration session, the first exposure session, and the second exposure session. The calibration session was a session intended to calibrate the anxiety measurement algorithm as described in section 3.

The main exposure sessions consisted of two free-speech dialogue interactions that included questions and responses from a virtual job interviewer to participants' answer in the setting of a job interview scenario. The interview was conducted once by a male and once by a female interviewer (Figure 4.5), which order was counterbalanced. In the static condition, the vr stressor % was set at 70% and did not change throughout the session. In the dynamic condition, the vr stressor % was initialized on a value of 70%, but was after this modified by the system targeting an anxiety reference value of 70%. Both exposure sessions lasted for 16 minutes each and every 4 minutes the system asked for a SUD score. This meant that update cycle of vr stressor % in dynamic condition was every 4 minutes. To limit the delay in response, K_b was set to 1. K_f was also set to 1, thereby assuming that after 4 minutes exposure participants would have responded on the stressor.

After participants completed each exposure session, they filled in questionnaires (i.e., IAQ, DEQ, and SAM). Furthermore, at the end of second exposure session, participants were also asked to complete the IPQ. The total time of the experiment was about 50 minutes.

During the experiment, all participants were exposed using a re-advancement version of the Delft Remote Virtual Reality Exposure Therapy (DRVRET) system [14]. This re-advancement includes new and longer dialogues, speech recognition, and a speech detection algorithm in the system. This re-advancement allowed participants to engage in an automatic free-speech dialogue conversation with a virtual job interviewer without the need for a human controller to control the virtual human. The experiment used a SONY HMZ-T2 Head Mounted Display (HMD). This HMD has a high definition screen resolution (720p) with a 50 degrees viewing angle that simulates a 720-inch screen seen at a 20-meter distance. The HMD was equipped with a custom-built head motion tracker

Table 4.2: Mean (*SD*) of the outcome measures: multimodal anxiety scale, sud score rating, heart rate, heart rate variability and length of speak; and the stressors: dialogue, eye gaze, and body posture in static and dynamic condition

	Static condition					Dynamic condition				
	Overall	Time slot (minutes)				Overall	Time slot (minutes)			
		0 - 4	4 - 8	8 - 12	12-16		0 - 4	4 - 8	8 - 12	12 - 16
Measurement										
Multimodal Anxiety (0% - 100%)										
Measurement*	48.71% (3.03%)	75% (6%)	60% (8%)	46% (6%)	14% (6%)	65.43% (2.21%)	72% (4%)	61% (5%)	54% (6%)	74% (7%)
Deviation**	-21.24% (4.05%)	5% (7%)	-10% (14%)	-24% (7%)	-56% (5%)	-4.82% (3.56%)	2% (6%)	-9% (8%)	-16% (5%)	4% (7%)
SUD Score (0 -10)										
Measurement	3.80 (0.69)	4.88 (1.08)	4 (1.02)	3.5 (0.88)	2.83 (0.87)	4.41 (0.77)	4.71 (1.04)	4.21 (1.14)	4.08 (0.97)	4.63 (0.82)
Deviation***	-29.15% (3.57%)	7% (4%)	-13% (6%)	-32% (6%)	-78% (7%)	-6.72% (3.27%)	3% (5%)	-16% (9%)	-19% (5%)	5% (6%)
Heart rate (bpm unit)										
Measurement	88.36 (2.75)	90.35 (2.95)	88.65 (2.75)	87.98 (2.96)	86.45 (2.88)	89.64 (2.47)	89.95 (3.36)	89.56 (2.91)	88.74 (2.02)	90.32 (2.53)
Deviation***	-34.55% (3.35%)	-10% (8%)	-23% (5%)	-41% (8%)	-64% (8%)	-8.15% (5.42%)	-4% (13%)	-12% (9%)	-15% (13%)	-2% (8%)
RMSSD (s)										
Measurement	54.16 (6.54)	50.73 (9.00)	52.66 (7.29)	56.63 (5.57)	59.38 (5.20)	48.25 (5.04)	47.71 (6.04)	48.41 (5.56)	49.55 (4.67)	47.34 (6.30)
Length of speak (s)										
Measurement	69.13 (4.16)	56.29 (6.58)	65.67 (7.29)	68.42 (11.28)	86.13 (9.50)	66.26 (4.48)	59.96 (6.08)	69.79 (10.69)	65.21 (7.79)	70.08 (8.29)
Stressors (0% - 100%)										
Dialogue		70%	70%	70%	70%		70%	82% (10%)	89% (9%)	96% (5%)
Eye gaze		70%	70%	70%	70%		70%	82% (8%)	90% (5%)	97% (4%)
Body posture		70%	70%	70%	70%		70%	82% (9%)	90% (4%)	97% (3%)

* The personalized multimodal anxiety scale internal used by the VRET system.
** The percentage of deviation from anxiety reference level (set at 70%). Minus sign means that anxiety drop below the reference value.
*** The percentage of deviation from individual measurement unit (SUD, heart rate) toward anxiety reference value (set at 70%). SUD score calculated using equation 2 and-heart rate calculated using equation 3. Minus sign means that anxiety drop below the reference value.

system with a 6 MHz update rate. The visualization and animation of the virtual (office) room and the virtual human were developed using 3D Studio Max and Vizard software. The DRVRET system ran on a Dell Precision desktop with Intel quad-core Q6700 @ 2.66 Ghz with 4 GB of RAM and NVidia Geforce FX 4600 graphic adapter running on Windows 7x64 bit.

4.6. DATA PREPARATION AND ANALYSES

To check the internal consistency for all items in the questionnaires, Cronbach's α were calculated. The SIAS, IAQ, and DEQ all showed high internal reliability with Cronbach's α values of 0.93, 0.87, and 0.75, respectively. For each of questionnaire overall scale was calculated based on the average of all items. To calculate the progression of the score on multi-modal anxiety scale over the time during the exposure, both SUD score and heart rate were combined using regression model that was created for each participant during pre-session calibration procedure. This resulted in a single anxiety measurement. Next, the deviation from the anxiety reference was calculated using Equation 4.8.

The response of individuals with less or more social anxiety was studied by dividing the participants into two groups: a lower and higher social anxiety group. These two groups were generated based on their SIAS's overall score data (M = 27.79, SD = 11.97). Participants who scored below the SIAS's mean were categorized as members of the lower social anxiety group and participants who scored above the SIAS's mean were categorized as members of the higher social anxiety group.

To analyse all the data (experiment data and R-scripts were available online at 4TU Centre for Research Data*), a series of multivariate, univariate analyses and *t-test* were conducted. A Greenhouse-Geisser correction was used when the sphericity assumption was violated. Furthermore, *post-hoc* analyses were conducted using Sidak correction to control for possible Type I Error inflation.

4.7. RESULTS

4.7.1. AUTOMATIC ANXIETY CALIBRATION SESSION

DURING the calibration session, 20 participants used the ideal calibration rule (Equation 4.1), 2 participants used the SUD score calibration rule (equation 4.2) and another 2 participants used the heart rate calibration rule (equation 4.3). None of the participants had to use the generic calibration rule (Equation 4.4). To evaluate participant's level of anxiety during the anxiety calibration session, series of *post-hoc* analyses were conducted. The results (Table 4.1) revealed that compared to the anxious condition, participants in the relax condition rated their subjective unit of discomfort significantly lower and had a significantly lower heart rate. Furthermore, during the relaxation condition, participant's anxiety decreased over time, while during the anxious condition participant's anxiety increased over the time.

4.7.2. ANALYSIS OUTCOME MEASURES

Mean and standard deviation of the outcome measure and stressors values collected in two experimental conditions are presented in Table 4.2. Figure 4.6 shows that while in the static condition overall anxiety dropped over time, in the dynamic condition it remained relatively stable (M = 65.43, SD = 2.21) centering around anxiety reference value. On average it deviated -4.82% (SD = 3.56) from the reference value. A similar pattern was observed for the 2 participants that used the SUD score only calibration rule (-1.25%, SD = 2.83), and 2 that used the heart rate only calibration rule (-5.12%, SD = 3.36).

A doubly MANOVA repeated-measures was conducted to test the overall effect of both static and dynamic system response conditions on participants' anxiety level, with system responses (static and dynamic) as well as the time-slot (moment of measuring) as the independent within-subjects variables and the two social anxiety groups as between-subject variable. The participants' SUD score rating, heart rate, heart rate variability (RMSSD) and length of speech were used as dependent variables. The results showed a significant overall main effect of static and dynamic system response conditions on participant's anxiety level (Table 4.3). Univariate analyses also revealed significant effect of both static and dynamic system response conditions on participant's SUD score rating, heart rate variability and length of speech. Moreover, effect on the heart rate was also

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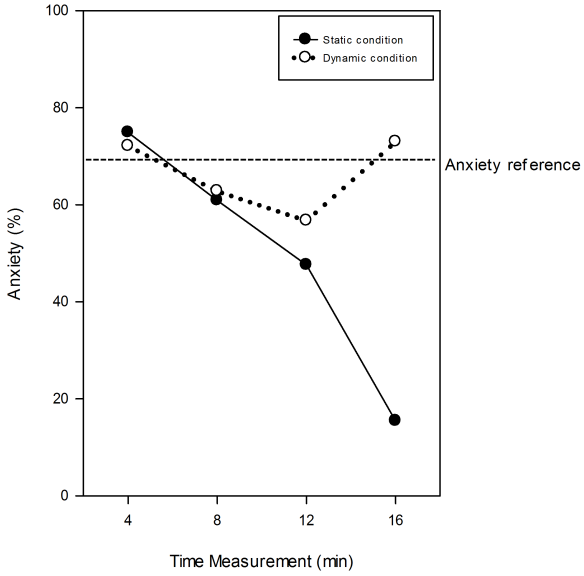

Figure 4.6: The anxiety progression from the 70% anxiety reference values during the exposure session, calculated by combining both SUD score and heart rate into a single anxiety measure using a linear regression model

found which approached the significant level of .05 (Table 4.3). These results suggest that the static and dynamic system responses were able to elicit different level of anxiety.

Furthermore, on participant's anxiety level the doubly MANOVA repeated-measures also revealed that overall there was a significant two-way interaction effect between the static-dynamic system responses condition and the time-slot (Table 4.3). Univariate analyses confirmed this finding for participants' SUD score, heart rate, heart rate variability and length of speak (Table 4.3). As Figure 4.7 shows, in the static condition anxiety dropped over time, SUD score and heart rate decreased and heart rate variability and length of speak increased. In the dynamic condition no such drop was observed.

A *post-hoc* test with Sidak correction was conducted to compare participants' SUD score rating, heart rate, heart rate variability, and length of speech in all four minutes time-slot measurement points for both static and dynamic system response conditions. As Table 4.4 shows, the decline in anxiety between two conditions was observed especially in last time slots. Furthermore, on average, in the first four minutes answers given in the static condition were shorter than in the dynamic condition.

Table 4.5 shows the results of *post-hoc* test with Sidak correction on measures in dynamic condition, comparing measurement obtained in the first slot with the ones obtained in later slots. With the exception of audio length, no significant difference was found between measurement in first and the last slot, suggesting anxiety return to the initial anxiety level after 16 minutes. For audio length, a significant increase was observed. Still as Figure 4.7 shows this increase was much lower that observed in the statis-

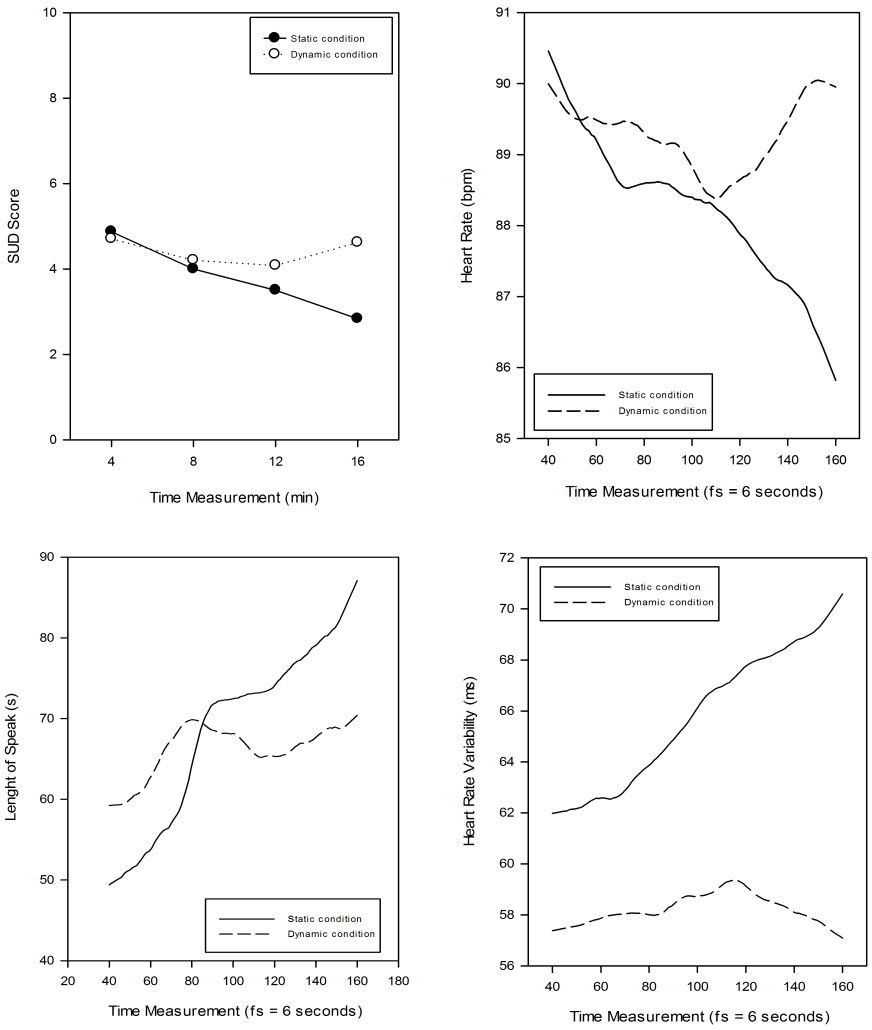

Figure 4.7: The continuous effect of static and dynamic system response conditions on participants' SUD score (**top-left**), heart rate (**top-right**), the length of speak (**bottom-left**) and heart rate variability (**bottom-right**) with six seconds sampling rate (*fs*)

Table 4.3: Multi- and univariate analyses with both static and dynamic system responses as within-subject factor and social anxiety group as between-subject factor on sud score rating, heart rate, heart rate variability and length of speak

Factors	Hyp. *df*	Error *df*	*F*	*p*	η^2
Overall					
System respond	4	19	7.84	0.001	0.62
Time slot	12	11	50.47	<0.001	0.98
Social anxiety group	4	19	20.34	<0.001	0.81
System respond × time slot	12	11	14.60	<0.001	0.94
System respond × social anxiety group	4	19	1.76	0.178	0.27
Time slot × social anxiety group	12	11	16.93	<0.001	0.95
System respond × time slot × social anxiety group	12	11	4.54	0.009	0.83
SUD score (0 - 10)					
System respond	1	22	15.34	<0.001	0.41
Time slot	3	66	38.82	<0.001	0.64
Social anxiety group	1	22	34.15	<0.001	0.61
System respond × time slot	3	66	12.99	<0.001	0.37
System respond × social anxiety group	1	22	2.43	0.133	0.10
Time slot × social anxiety group	3	66	15.05	<0.001	0.41
System respond × time slot × social anxiety group	3	66	0.42	0.742	0.02
Heart rate (bpm)					
System respond	1	22	3.98	0.058	0.15
Time slot	3	66	36.64	<0.001	0.62
Social anxiety group	1	22	27.88	<0.001	0.56
System respond × time slot	3	66	15.79	<0.001	0.42
System respond × social anxiety group	1	22	1.32	0.262	0.06
Time slot × social anxiety group	3	66	7.89	<0.001	0.26
System respond × time slot × social anxiety group	3	66	0.70	0.557	0.03
Heart rate variability (ms)					
System respond	1	22	7.41	0.012	0.25
Time slot	2.10	46.27	28.82	<0.001	0.57
Social anxiety group	1	22	50.10	<0.001	0.69
System respond × time slot	1.72	37.80	17.46	<0.001	0.44
System respond × social anxiety group	1	22	0.89	0.354	0.04
Time slot × social anxiety group	2.10	46.27	6.36	0.003	0.22
System respond × time slot × social anxiety group	1.72	37.80	0.55	0.553	0.02
Length of speak (s)					
System respond	1	22	9.07	0.006	0.29
Time slot	3	66	58.06	<0.001	0.73
Social anxiety group	1	22	0.15	0.702	0.01
System respond × time slot	3	66	19.24	<0.001	0.47
System respond × social anxiety group	1	22	5.19	0.033	0.19
Time slot × social anxiety group	3	66	17.82	<0.001	0.45
System respond × time slot × social anxiety group	3	66	3.37	0.023	0.13

Note: Hyp *df* = Hypothesis degree of freedom; Error *df* = Error degree of freedom; *F* = Fisher's *F* ratio; *p* = probability; η^2 = effect size

Table 4.4: Comparison between static and dynamic system respons for the different measuring time-slot

Time-slot (minutes)	Static condition *M*(*SD*)	Dynamic condition *M*(*SD*)	*t*(23)	*p*	*d*
SUD score (0-10)					
00 – 04	4.88 (1.08)	4.71 (1.04)	0.78	0.905	0.16
04 – 08	4.00 (1.02)	4.21 (1.14)	-0.84	0.878	-0.17
08 – 12	3.50 (0.88)	4.08 (0.97)	-2.12	0.169	-0.43
12 – 16	2.83 (0.87)	4.63 (0.82)	-7.69	<0.001	-1.57
Heart rate (bpm)					
00 – 04	90.35 (2.95)	89.95 (3.36)	0.95	0.823	0.19
04 – 08	88.65 (2.75)	89.56 (2.91)	-2.11	0.173	-0.43
08 – 12	87.98 (2.96)	88.74 (2.02)	-1.82	0.288	-0.37
12 – 16	86.45 (2.88)	90.32 (2.53)	-5.86	<0.001	-1.20
Heart Rate Variability (ms)					
00 – 04	50.73 (9.00)	47.71 (6.04)	1.51	0.463	0.31
04 – 08	52.66 (7.29)	48.41 (5.56)	2.27	0.125	0.46
08 – 12	56.63 (5.57)	49.55 (4.67)	4.54	<0.001	0.93
12 – 16	59.38 (5.20)	47.34 (6.30)	6.99	<0.001	1.43
Audio Length (s)					
00 – 04	56.29 (6.58)	59.96 (6.08)	-3.06	0.022	-0.62
04 – 08	65.67 (7.29)	69.79 (10.69)	-1.36	0.565	-0.28
08 – 12	68.42 (11.28)	65.21 (7.79)	1.45	0.504	0.30
12 – 16	86.13 (9.50)	70.08 (8.29)	5.48	<0.001	1.12

Note: *M* = Mean; *SD* = standard deviation; *t* = computed value of t test; *p* = probability; *d* = Cohen's measure of effect size

tic condition.

The doubly MANOVA repeated-measures also revealed that there was a significant overall main effect for the social anxiety groups, ($F(4,19) = 20.34$, $p < 0.001$, $\eta^2 = 0.81$). Furthermore, the univariate test (Table 4.3) revealed a significant difference between the two social anxiety groups on SUD score rating, heart rate and heart rate variability. As depicted in Figure 4.8, the higher social anxiety group rated their SUD score significantly higher and revealed significant higher heart rate compared to the lower social anxiety group. Furthermore, the higher social anxiety group also showed a significantly lower time-domain heart rate variability compared to the lower social anxiety group. No significant different was found in length of speak. The doubly MANOVA repeated-measure also found that overall there was a significant two-way interaction effect between time-slot and the social anxiety groups on the anxiety level (Table 4.3). Univariate analyses confirmed this two-way interaction effect in: the SUD score, heart rate, heart rate variability, and the length of speech. As depicted in Figure 4.8, the difference between higher and lower social anxiety groups seemed to decrease over time for the SUD score, heart rate, and heart rate variability, while for the length of speech no such pattern was observed.

4.7.3. ANALYSIS PROCESS MEASURES

Mean and standard deviation of process measures collected in two experimental conditions are presented in Table 4.6. Compared to the dynamic condition, in the static condition participants rated their dialogue experience more positively and had a significantly more pleasant feeling and positive attitude toward the interviewer. Also the virtual human was perceived as more pleasant, less aroused and less dominant. Furthermore,

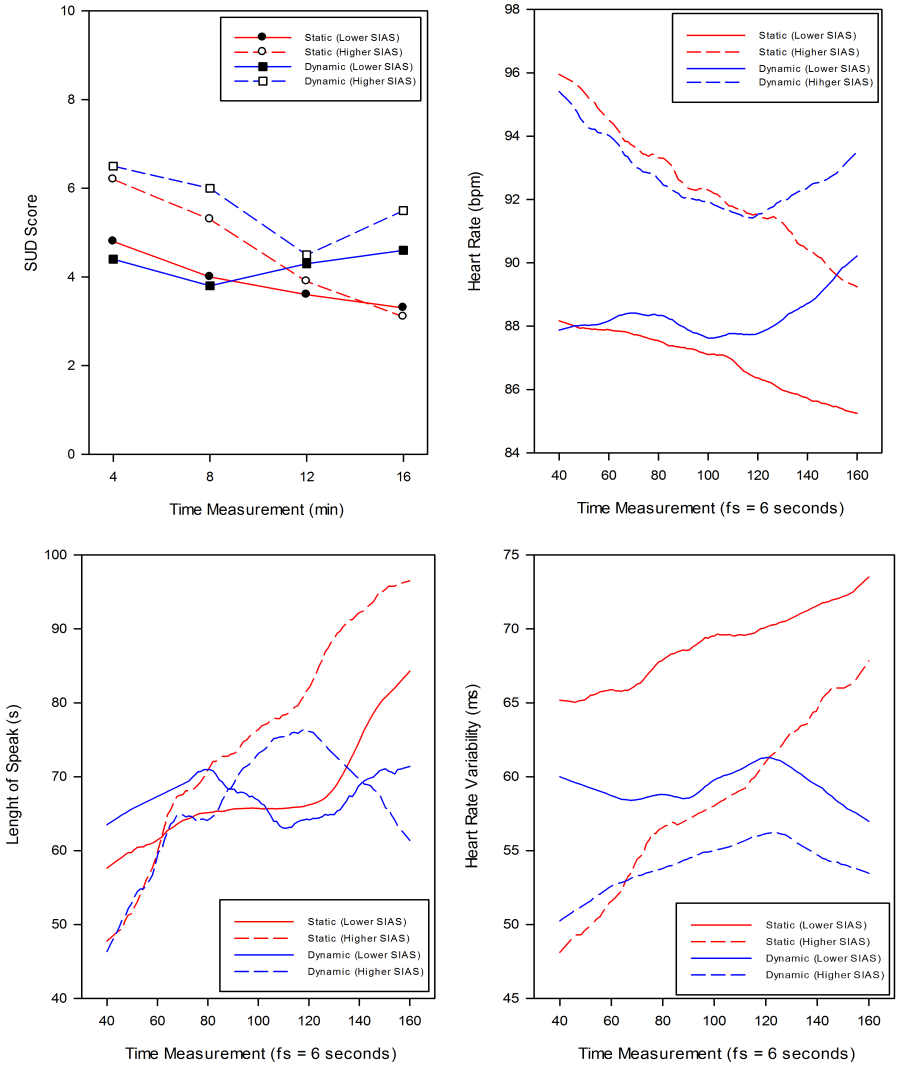

Figure 4.8: The continuous effect of static and dynamic dialogue stressor on two participants group's SUD score (**top-left**), heart rate (**top-right**), the length of speak (**bottom-left**) and heart rate variability (**bottom-right**)

Table 4.5: Comparison between first time-slot and second, third and fourth time-slot in dynamic condition

Time-slot (minutes)	1st time-slot *M*(*SD*)	time-slot *i* *M*(*SD*)	*t*(23)	*p*	*d*
SUD score (0-10)					
04 – 08	4.71 (1.04)	4.21 (1.14)	3.14	0.014	0.64
04 – 12	4.71 (1.04)	4.08 (0.97)	2.46	0.064	0.50
04 – 16	4.71 (1.04)	4.63 (0.82)	0.46	0.956	0.09
Heart rate (bpm)					
04 – 08	89.95 (3.36)	89.56 (2.91)	1.10	0.632	0.22
04 – 12	89.95 (3.36)	88.74 (2.02)	2.72	0.036	0.56
04 – 16	89.95 (3.36)	90.32 (2.53)	-0.82	0.807	-0.17
Heart Rate Variability (ms)					
04 – 08	47.71 (6.04)	48.41 (5.56)	-1.12	0.615	-0.23
04 – 12	47.71 (6.04)	49.55 (4.67)	-3.03	0.018	-0.62
04 – 16	47.71 (6.04)	47.34 (6.30)	0.34	0.982	0.07
Audio Length (s)					
04 – 08	59.96 (6.08)	69.79 (10.69)	-4.97	<0.001	-1.02
04 – 12	59.96 (6.08)	65.21 (7.79)	-2.16	0.120	-0.44
04 – 16	59.96 (6.08)	70.08 (8.29)	-5.69	<0.001	-1.16

Note: *M* = Mean; *SD* = standard deviation; *t* = computed value of t test; *p* = probability; *d* = Cohen's measure of effect size

Table 4.6: Mean and *SD* of the process measures record in static and dynamic condition

Measure	Static condition *M*(*SD*)	Dynamic condition *M*(*SD*)	*t*(23)	*p*	*d*
Total DEQ	38.62 (2.36)	31.66 (2.23)	7.76	<0.001	1.58
Total IAQ	23.17 (3.75)	20.88 (4.30)	3.94	<0.001	0.80
SAM Participant					
- Valence	3.08 (0.65)	2.67 (0.56)	3.50	0.002	0.71
- Arousal	2.75 (0.53)	3.13 (0.54)	-2.23	0.036	-0.45
- Dominance	3.33 (0.82)	2.83 (0.56)	3.71	0.001	0.76
SAM Avatar					
- Valence	2.46 (0.51)	2.00 (0.72)	2.70	0.013	0.55
- Arousal	2.83 (0.56)	3.50 (0.72)	-3.00	0.006	-0.61
- Dominance	2.67 (0.92)	4.04 (0.69)	-4.89	<0.001	-1.00

Note: *M* = Mean; *SD* = standard deviation; *t* = computed value of t test; *p* = probability; *d* = Cohen's measure of effect size

participants rated their own emotion as more pleasant, less aroused but more dominant.

The participants' level of presence was analyzed by comparing participants' overall IPQ score with online IPQ score dataset for stereo HMD visual stimuli (downloaded on April 09th, 2015. For comparison data see: http://www.igroup.org/pq/ipq/data.php).

The overall IPQ score ($M = 47.29$, $SD = 2.48$) was significantly higher ($t(60.26) = 3.53$, $p < 0.001$) than the overall online IPQ score dataset ($M = 39.09$, $SD = 16.94$). This result suggest that the virtual environment provided in this experiment successfully establishing a significant amount of presence compared to the reported presence in other online virtual world. Furthermore, there was no significant difference ($t(22) = -0.51$, $p = 0.617$) found between higher and lower social anxiety groups on the overall level of presence.

4.8. CONCLUSION AND DISCUSSION

4.8.1. MAIN FINDING

THE findings of the automatic anxiety calibration revealed that participants' self-reported anxiety and heart rate was lower in the relaxation condition than in the anxious condition, supporting thereby the first hypothesis. Detailed analysis revealed that it was possible to establish a personalized anxiety measure for all participants. For a large majority (83%) this measure included both self-reported anxiety as well as heart rate data.

The other main conclusion is that anxiety level of participants could be regulated. The findings showed that in a situation without anxiety regulation, anxiety dropped as indicated by lower self-report anxiety, lower heart rate, more heart rate variability, and longer answers (Table 4.3 and Figure 4.7). On the other hand, the findings also showed that with regulation anxiety could be maintained around a pre-set anxiety reference value of 70%. On average the anxiety measured deviated only -4.82% from the reference value. Interestingly, at the end of the session the anxiety deviated only 4% of the reference value. No indication was found that regulation ability was reduced if the axiety measure was only based on a single feature, i.e. only SUD or only heart rate. Whereas measures included in the multi-modal measure, i.e. self-reported anxiety and heart rate, seem to be at the same level at the end and start of the session, this was not the case for the length of the answers, which increased over time. This might suggest that measures directly included in a regulation process can also be more regulated. In addition to this, future research might also study if specific measures are more susceptible to latency effects. Long latency would require adjustment of the forward proportionality constant (K_f). Still, these findings do support the second hypothesis as they demonstrate the effectiveness of the anxiety regulation mechanism. The results also show that anxiety level was maintained by steadily increasing the stressor levels related to dialogue, eye gaze and body posture of the virtual human.

The results also confirm observations reported in the literature regarding the ability to evoke anxiety in a simulated social scenario. In this regard, the results of the overall measures are of interest where participants in the anxiety regulated condition, i.e. dynamic condition, can be seen as experiencing higher anxiety, and those in the static condition as experiencing lower anxiety. Like Hartanto et al. [5] and Chao et al. [69] previously reported, in the higher, compared to the lower anxiety evoking condition, participants rated the dialogue more negatively, reported less pleasant feeling, i.e. lower valence, more aroused, and less dominant, and had a more negative attitude towards the virtual human. Furthermore, the emotion of virtual human less pleasant, and more aroused. The analysis of lower and higher social anxiety also confirm previous observations by Hartanto et al. [5], Chao et al. [69] and Morina et al. [2]. They also reported that compared to their lower social anxiety group, their higher anxiety group experienced more anxiety. In this study self-reported anxiety and heart rate was higher, while their heart rate variability was lower.

Furthermore, on average all participants reported a considerable level of presence compared to presence level reported by other studies. This is a promising observation, given that this study consisted of 16 minutes, fully automatic dialogue with a virtual avatar without direct intervention of human operator.

The main scientific contribution of this study lies on the development and validation

of an automatic feedback-loop mechanism as an algorithm to regulate the anxiety level. This automatic feedback regulator mechanism will be useful as a base platform to develop an automatic virtual reality exposure therapy system where less therapist involvement is needed to control the system, something desirable when considering a remote VRET system. Besides the psychotherapy domain, anxiety regulation systems might also beneficial for other domain such as Trier Social Stress Test (TSST) training [70,71], negotiation simulation [72], job interview training [5], presentation training [73], or serious gaming [74] since all these domains can benefit from automatic regulated feedback-loop emotion mechanism.

4.8.2. LIMITATION AND FUTURE WORK

To appreciate the study's findings, it is important to reflect on its limitations as well. A first limitation to consider is that the virtual human always took the lead in the dialogue conversation. This algorithm was chosen to prevent the dialogue becoming to wide and out of topic. Some individuals with social anxiety disorder, however, might specifically fear a situation where they need to start and lead the dialogue conversation. This element was not targetted in the simulated dialogues. A second limitation of the experiment is that it focused only on a job interview scenario, where individual with social anxiety might fear a range of social scenarios. However, the experimental findings might still be generalizable to social situation that include a dialogue. The last limitation to mention is that this study included only a non-patient sample. Nevertheless, if anxiety is considered as a continuous scale, the different found between lower and higher social anxiety individual in this study might be also be generalized to individuals higher up in the social anxiety scale.

The work presented in this paper can be extended in several ways. For clinical purposes, it would be valuable to study how the anxiety regulation should be implement to optimize it for therapeutic goals. In the experiment, the reference value remained constant, which is undesirable when treating a patient. Instead it might be more desirable to offer patients exposure to situations where their anxiety is first brought to a specific reference value, after which virtual stressors are no longer changed, and patients can experience the decline in their anxiety as habituations to the stressor sets in. Furthermore, the level of anxiety during treatment often needs to change within or between sessions as it depends on factors such as the specific goal of the therapeutic step (e.g., habituation vs. challenging relevant cognitions) or course of treatment (e.g., as treatment advances, longer high anxiety levels might be desirable). Another challenge is the initial value of the virtual stressors. Strong initial anxiety deviation from reference value is undesirable. Whereas creating initially a too high anxiety level should clearly be avoided, having patients exposed for a long period on a too low level of anxiety might reduce the acceptance of therapy. Therefore, it might prove essential to develop a measure technique that quickly provides anxiety information, as this would allow the regulation system quickly to adjust the virtual stressors and therefore reduce the initialization process. Another challenge is the mapping between the anxiety deviation, the stressor adjustment ratio, and individual anxiety stressors. In the experiment this was arbitrarily mapped as a *one-to-one* relation. This caused an anxiety deviation of 10% always to lead to a 10% increase of the maximal capacity of an individual stressor. However, in theory a stressor might

have the ability to increase anxiety level well above the 100% anxiety scale that was initially calibrated on an anxiety level a person found still tolerable. As a person's response towards a stressor is initially unknown, modification to a stressor level should ideally only be small (i.e. small K_b) and the person's response quickly measured. The later need to relate to how quickly a person actually responds to a stressor (K_f). Finding a strategy to balance these two issues (K_b, K_f) is crucial.

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5

HOME-BASED VIRTUAL REALITY EXPOSURE THERAPY SYSTEM WITH VIRTUAL HEALTH AGENT SUPPORT

To increase the accessibility and efficiency of virtual reality exposure therapy (VRET) this paper proposes a system for home-based use where patients with social phobia are supported by a virtual health agent. We present an overview of our system design, and discuss key techniques such as (1) dialogue techniques to create automated free speech dialogue between virtual characters and patients in virtual reality worlds; (2) a multi-modal automatic anxiety feedback-loop mechanism to control patients' anxiety level; and (3) motivational techniques applied by a virtual health agent. The system was evaluated in a pilot study where five patients with social phobia utilized our home-based VRET system. The results showed that the system was able to evoke the required anxiety in patients and that over time self-reported anxiety and heart rate gradually decreased as expected in exposure therapy.

***Keywords**: Virtual reality therapy, virtual coach, virtual health agent, behaviour change support system, social anxiety disorder, self-therapy.*

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5.1. INTRODUCTION

SOCIAL phobia is one of the most often occurring mental disorders, with reports that estimate this to affect around 13.3% of the US population [1] during their life-time. Patients with social phobia fear social situations in which they may be scrutinized by others [2], for example when having a conversation with someone, being observed, meeting someone new, or giving a presentation. Exposing patients in virtual reality to these social situations has been suggested [3] as a treatment for this disorder. As for other anxiety disorders, the development of virtual reality exposure therapy (VRET) systems mainly focuses on systems that can be used in a health clinic where a therapist directly controls the system when the patient is exposed [4]. However, with an ever-increasing demand for more efficiency and accessibility, it is desirable to be able to offer this treatment at the patient's home. We therefore propose a home-based VRET system where social phobia patients are also supported by a virtual health agent. In the design of this system three specific challenges were ad-dressed that are discussed in this paper. First, how to create a long conversation with a virtual character to let patients experience the required social anxiety? Second, how do you automatically control the patient's anxiety throughout a conversation with virtual characters? Third, how could a virtual health agent motivate a patient to continue with the therapy? We also present the results of a pilot study in which individuals with social phobia utilized our home-based VRET system.

5.2. RELATED WORK

PROVIDING treatment for social phobia over the Internet is possible. For example, in a randomized controlled trial, Gallego et al. [5] found a significant improvement in patients receiving a remotely delivered treatment using non-interactive exposure video over the internet. The patients' fear of public speaking, work impairment, and avoidance behavior decreased. Instead of using video exposure, others [6] have suggested a system that allowed the therapist to control VRET from a remote location over the internet. Still, this set up required the therapist to be actively involved.

At least part of the exposure does not require the presence of a therapist. In cognitive behavioral therapy (CBT), homework exposure exercises have been employed as an integral component in the treatment for several anxiety disorders such as obsessive compulsive disorder, post-traumatic stress disorder and social phobia [7]. Even though effective for some intervention [8], lack of an active involvement of the therapist during treatment has been associated with reduced therapeutic efficacy, such as in relation to depression [9]. In self-therapy settings, patients usually rely on persuasive power of the homework-exercise itself. Whereas when therapists are involved, patients are often also influenced by the therapeutic alliance, even with virtual exposure therapy [10]. This brings forward the questions whether such an effect could also brought about with a virtual health agent?

The presence of a virtual health agent can have a positive effect on treatment outcome [11]. These agents often aim to guide individuals through a specific task thereby stimulating positive behaviour, increasing motivation and adherence [12,11]. Typically, the health agent applies persuasive techniques to change people's attitude and behaviors [13].

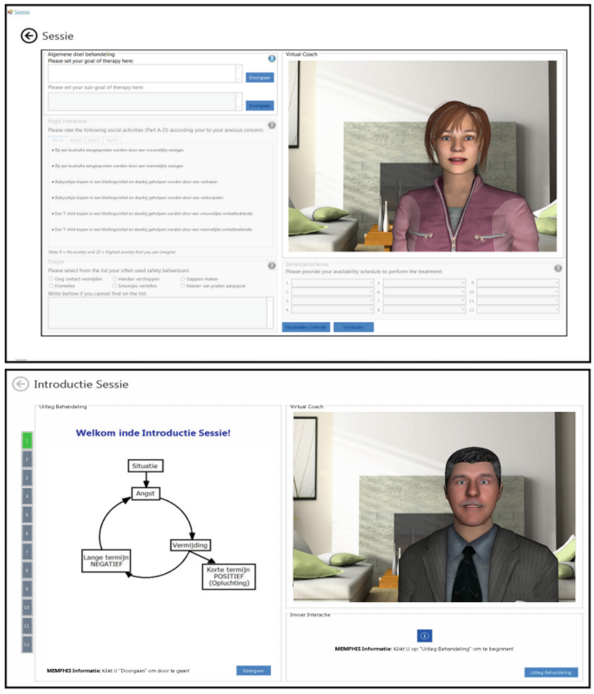

Figure 5.1: The female virtual health agent guiding patient to set the therapy goals (top), and the male virtual health agent providing interactive psycho-education (bottom)

5.3. SYSTEM DESIGN

THE entire concept of the home-based VRET system was review in a series of discussions with eight clinical psychologists. Based on their input, a number of scenarios were written and again reviewed by eight clinical psychologists, leading eventually to an implemented system called the Memphis system [14]. The system consists of three main entities: (1) the virtual health agent, (2) the virtual reality system and (3) the therapist application.

5.3.1. THE VIRTUAL HEALTH AGENT

The main objective of the virtual health agents (Figure 5.1) was to guide the patient through the various steps of the therapy and motivate them to continue with the therapy. Guiding the patients through the therapy involved explaining patients how to assemble the system so it could be used. Patients received a set of video's and instructions manuals on how to connect the various hardware elements such as: head mounted display (HMD), head tracker, heart rate device, internet dongle, security dongle, and microphone. Once the Memphis system was started, the virtual health agent helped the patient to calibrate and test the system, for example, training the speech recognizer, calibrating the anxiety measurement, testing sound and internet connection, wearing the heart rate device and finally setting up the HMD and the head position tracker.

Besides guiding patients through the technical aspect of the system, the virtual agent

also introduced the patients to the therapy itself. The first motivational strategy the agent applied was to help patients to formulate an achievable treatment goal. After explaining the purpose of setting goals and also giving some example, the agent asked patients to enter their goal. Interpreting this textual formulated goal and providing feedback by the agent was regarded as no achievable. Instead the agent used the strategy of empowering the patients to do this themselves. In other words, after entering the goal, the agent gave patients criteria to evaluate their own goal, for example, achievable, concrete, but also not too easy. Again, it provided this with some examples. Afterwards patients were asked again to reflect on their goal. This procedure was repeated when helping patients to formulate specific sub goals. This information together with information the agent asked about anxiety for specific social situations, and avoidance behaviors were automatically sent through a server to the therapist, who could use the information to create the anxiety hierarchy for social situations and a treatment plan. The second motivation strategy the agent applied was psycho-education. The agents explained what social anxiety disorder is, and the mechanisms underlying it. The agents also explained the therapy and what patients could expect. Besides this general information, the agent also explained in each session all the steps, e.g. filling out questionnaires, conducting virtual reality exposures, and reflecting on the outcome and progress. In the last session, the agents also helped the patients to develop relapse prevention strategies in a similar manner as the agent initially had supported the patient to formulate a treatment goal. The third motivation strategy that the agent applied was helping patients to reflect on their reactions during the virtual reality exposures, and also their overall progress during the treatment. For this the agent used an expert system approach using a therapeutic social anxiety knowledge base. The knowledge base was written and validated by clinical therapists. After patients were exposed in a virtual world, the agent provided patients with an interpretation of the collected heart rate data, self-reported anxiety, and stress level manipulation in virtual world. Internally the agents used eight templates to characterize the data of anxiety progress during the exposure, and three templates to characterize the stress level manipulation. Interpretations were linked to the 24 cells of this a 8 x 3 matrix. When formulating the reflections, the agent started with explaining what information was shown by the graphics on the screen. This was followed by the data interpretation, possible speculations about the causes of this result and elements of psycho-education. The agent finished with an encouraging remark aiming to improve patient's self-efficacy. The following is an example translated from Dutch of what the agent said: *"After the exercise in the virtual world we can now look together at the results that were collected. At the screen you can see several graphs.The last graph shows how difficult the system has tried to make it for you. if I look at the graphs, there are two things I notice. First, your anxiety level, the combination of your heart rate and self-reported anxiety, started relative high but reduced during the exercise. Secondly, the number of social challenges remained constant during the entire exercise. This exercise nicely demonstrates that after a while your anxiety naturally deceased. This is exactly what we try to achieve with this exercise. Very good! Nice result!"* To avoid repetition of agent reflection over time, each cell include several alternative formulations of what the agent could say.

The last motivation strategy the agent applied was to provide patients with a reflec-

Figure 5.2: Examples of seven virtual scenarios supported by the Memphis system (left to right). Top: Participating in an English class, having appointment in a restaurant, middle: being ask to participate in a survey, buying t-shirt in a shop, meeting a blind date in a restaurant, and bottom: having presentation in a class, meeting a stranger in a bus stop

tion of their overall treatment progress. For this, the agent looked at the overall anxiety level of the last three sessions and the sessions before this. As with the reflection after the exercises in the virtual world, the agent used a number of templates to characterize the recorded anxiety level across the sessions. Important was also that given the number of exercises scheduled and completed, the agent could recommend patients to contact the therapist if the therapy does not seem to work. Again, an example of a reflection that the agent could offer: *"Let's look at a number of things. First, if I look at the list with exercises, I can see that you have already completed 10 exercises, you are working currently on a new exercise, and that eight other exercises have been planned for you. This is very good! Secondly, if I look at the averages of the self-reported anxiety scores for the last 3 sessions I see scores that are relatively low. In the sessions before that, the anxiety scores were relative low... Because you have finished more that 60% of the anxiety hierarchy, is might be a good idea to discuss this with your therapist. It is important to find exercises that evoke anxiety. Also, it is important that you do not use anxiety avoidance strategies during the exercise..."*

5.3.2. THE VIRTUAL REALITY SYSTEM

VIRTUAL SOCIAL SCENARIO

The Memphis system provided 19 different virtual reality social scenarios, such as meeting a blind date in a restaurant, a job interview, visiting a doctor, talking to a stranger at a bus station, buying a t-shirt, and meeting a stranger at a party (Figure 5.2). All social scenarios were selected and developed to elicit social anxiety. They are also often used and suggested for exposure exercise in real life [15].

DIALOGUE TECHNIQUES

A key component of the system was to expose patients to free natural dialogues. As this was a home-based system, a dialogue should unfold without the need for direct human control, which is often not the case in current systems. Our system therefore employed key word recognition and speech detection technology. Each dialogue lasted around 18 minutes. To avoid an ever-broadening dialogue, the virtual characters always took the lead in the conversation, by asking the patients questions, and responding to patient's reaction. In these dialogues there was no room for questions from the patients. Therefore, patients were instructed not to ask questions to the virtual characters.

On average, each dialogue consisted of 78 dialogue units (i.e. **[avatar's question]** → **[patient's answer]** → **[avatar's response]**). Where obvious keywords could be expected in the patient's answer, the system searched for them in the patient answers. When they were detected, the virtual character gave a response directly related to patients' answers, for example: [foreigner character] *"when traveling with a train, how do I know I have to get out of the train?"* If answer of patients included the word "announcement", the virtual character would say: *"Ok than I pay attention to that in the train"*. In some cases characters' response was not appropriate, for example, when the wrong keyword was detected. This was however considered acceptable, as the objective was to exposure patients to social situations that would evoke anxiety, and not to expose them to flawless dialogues. By using keyword detection at some places in the dialogue, the hope was to give patients the illusion that character reacted intelligently towards their answers.

The majority of the virtual characters' responses however were not based on keyword detection. Instead, the characters provided responses that patients might think related to their answer, but were in fact independent of their answer. For example, [shop assistance] *"Can you also specify to me the price range that you're aiming for?"* After which an answer of the patient would follow. The virtual character would again respond to this answer *"Well, that's fine"*. For the responses it was anticipated that patients would assume that virtual characters would adhere to cooperative principles [16]. In other words, virtual characters and patients pursued mutual conversational goals and the character would try to provide relevant responses and avoid ambiguity. Furthermore, individuals often heavily rely on the process of interfering. In other words, they would assign meaning to the response of the virtual characters in light of the context of the dialogue and social setting. Table 5.1 provides a list of specific strategies that were used to create character responses.

A potential avoidance strategy patients might apply is to provide short answers to avoid exposure. To address this behavior the system monitored the length of patients' answers. Hence, when a patient gave a short answer, the virtual character engaged the

Table 5.1: List of dialogue techniques employed in the Memphis VR dialogue system

Dialogue Techniques	Example
Create topic blocks in the story line to avoid repetition in questioning. Blocks start with a monolog where the avatar provides information about him or herself, followed by questions the topic.	Block 1: [avatar talking about his family extensively] → [continue with questions about patient family] → Block 2: [avatar talking about his holiday last summer extensively] → [continue with questions about patient summer holiday] → etc.
Create generic avatar's respond that fit to any participant's answer.	Avatar: "*Hi, it seem that you're looking for someone, may I join you?*" → Patient: [answer] → Avatar: "*okay*"
(Dis)agree on what the patient said.	Avatar: *"What do you think about the climate change now days?"* → Patient: [answer] → Avatar: "*Great! I agree with you in this case*"
State an attitude or emotion towards the answer.	Avatar: *"I've been waiting for my food for 20 minutes now. The service is really slow here, what do you think?"* → Patient: [answer] → Avatar: "*Ah, I see. I am glad that you mention that!"*
Reflect on your original question, e.g. it was not relevant.	Avatar: "*Do you have OHRA health insurance or do you have another private health insurance?*" → Patient: [answer] → Avatar: "*OK, I understand that, it does not matter anyway*."
State an opinion.	Avatar: "*What do you think is the most interesting thing to see in the Netherland?*" → Patient: [answer] → Avatar: "*Yeah, I think visiting a traditional cheese factory, or clogs shop is a nice experiences.*"
State (mis)understanding of patient answer, and extend response with own information.	Avatar: "*What do you think about Amsterdam public transport right now?*" → Patient: [answer] → Avatar: "*Ok, I see your point. I also have pretty similar thoughts since I used it a lot the last couple of years.* "
State an opinion based on your beliefs, emotion or perceptions.	Avatar: "*What make you a good team leader?*" → Patient: [answer] → Avatar: "*Yeah, but honestly I feel that you're not ready yet to become a good team leader by judging your answer and your current experience"*
Makes a statement that is always true in relation to the topic.	Avatar: "*Are you feeling under any pressure or stress lately?*" → Patient: [answer] → Avatar: "*Okay, please remember that too much stress can affects your health."*

patients into a dialogue that encouraged the patient to provide longer answer, for example, *"It is not quite clear to me. Can you explain further?"*, *"What do you mean by that?"*, *"I have plenty of time here, can you explain it to me a bit more?"*, or *"Now you make me curious, tell me something more."*

THE PHOBIC STRESSORS

As a patient's anxiety response towards fear stimuli varies, the system deployed several phobic stressors in each virtual world. First, the dialogue units could either be positive or negative. Controlling the ratio of positive and negative dialogue units has been demonstrated as a key function to induce different level of anxiety [17]. A positive dialogue unit meant a dialogue that consisted of a friendly, affirmative or enthusiastic type of question and avatar response, such as *"I like to know your taste music, what kind of music do you like?"* and was followed by the avatar's response to the patient's answer *"Cool! Nice taste of music!"*. On the other hand, the negative dialogue unit meant that the dialogue was

formulated in an unfriendly, unenthusiastic and criticizing question and response, for example *"I don't think that you have a good taste of music, but in case I'm wrong, can you tell me what type of music you like?"* followed by the avatar's response *"Mmm... as I have expected, you know nothing about good music!"*. A second type of phobic stressors was the avatar gestures, for example the gaze of the avatar. As mentioned in other studies [18], (intense) direct eye gaze can evoke anxiety. Therefore the virtual characters also have the capability to stare at patients, look away, or simulate turn taking gaze behavior in a conversation. Besides gaze behavior, body posture of an audience [19], e.g. an interested audience or an audience that is bored, were used in public speaking scenarios.

THE ANXIETY FEEDBACK-LOOP

The system regulates patients' anxiety level by monitoring their anxiety and in a real-time fashion adjusting phobic stressors in the virtual world to reach the desired anxiety level as set by the therapist prior to a session. To monitor anxiety level, the system used both self-reported anxiety and a physiological measurement in the form of an automatically collected Subjective Unit of Discomfort (SUD) scale using speech recognition technology [20], and heart rate (bpm unit) using Zephyr HxM heart rate monitoring device. Both measurements were collected every four minutes during the exposure. Furthermore, using an individualized linear regression function, these two different modality measures were internally, at run-time, combined into a single anxiety measure on which the system acted. As patients vary on how their anxiety is expressed in the two anxiety measures, a calibration procedure was used in the first session of the therapy. Imaginary exposure was used to determine a patient anxiety response in a low anxiety and high anxiety situation. Using relaxing sounds clips, a patient was asked to relax for four minutes while SUD and hear rate data was collected. Next, the patient was asked to imagine giving a presentation and push him or herself to the highest, but still tolerable, level of anxiety using various sound clips of an audience (i.e. from a nice, quiet audience to a loudly boo-ing audience). Again anxiety data was collected for again a period of four minutes.

The automatic feedback loop used the personalized anxiety measure to regulate the patient's anxiety level. Before a session, therapists set the patient's initial target range for the patient's anxiety by defining the lower and upper bounder. At the start of a virtual reality (VR) exposure, the system increased or decreased the patient's anxiety to a level within the target range. The system did this by gradually increasing or decreasing the number or the degree of the phobic stressors in the virtual world. Once the patient's anxiety was within the target range, phobic stressors remained constant, or were reduced if patient's anxiety exceeded the target range. This regulation mechanism allowed patients to experience that their anxiety would naturally decline over time, and ensured that patients would not experienced an undesirable high level of anxiety for a long time.

THE THERAPIST APPLICATION

The therapist application was a standalone application used by the therapist to interact with their patients. Using this application, therapists were able to create a personalized treatment plan for a patient, monitor the patient's progress during the treatment by evaluating the questionnaires, SUD score and heart rate results (Figure 5.3), exchange

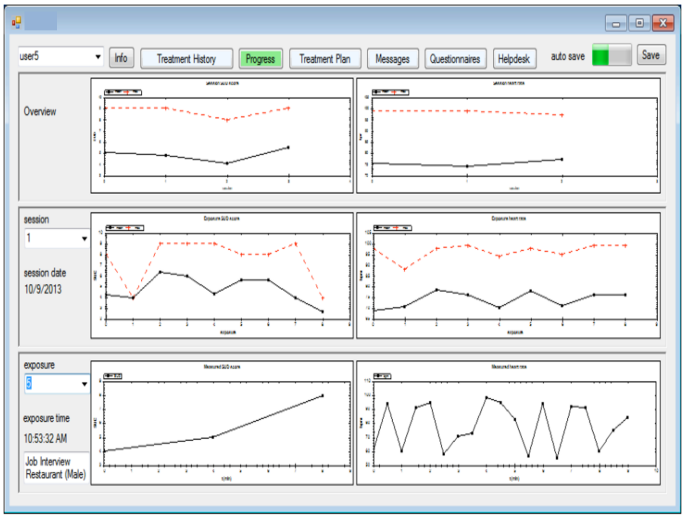

Figure 5.3: Monitoring the patient's progress during the treatment by evaluating the SUD score and heart rate results in the therapist application

personal messages with the patient using integrated e-mail services, creating and adjusting the treatment schedule, write a patient log book and relapse prevention strategy, and find the Memphis helpdesk contact information in case there is a technical problem. Once a therapist registered a session schedule and a treatment plan in the system, patients could start their treatment at home using the Memphis system.

To support the interaction and communication between the therapist application and the virtual coach application, a secure and centralized database server was established. This database server records all occurring events during the treatment, for example: recording the psychological measurement data, store all questionnaires data, store therapist – patient messaging activities. To ensure security ISO standards on the medical informatics security, such as ISO27001, ISO9001, ISO14001, but also the national guideline (NEN7510) were consulted and work procedures were formulated. Also, prior to treatment both therapist and patients received personalized encryption and decryption keys, which they had to plug into their computer. All data stored on the server and data exchange between server and the therapist and patient application was encrypted using these keys.

5.4. EVALUATION

SYSTEM operation and testing the usability of the system was done with a group of 5 university students and staff (non-patients) and an experimenter acting as a therapist. This test was conducted on a single set of hardware (Dell Inspiron 7720 laptop running Windows 7 64 bits). The tests revealed no serious operational or usability problems. The next step, therefore, was to examine the system in a small pilot study with actual patients, a first step towards larger scale clinical trial. The aim of the pilot study was to examine whether the system could evoke social anxiety and result-ed over time in

anxiety reduction when social phobic patients were exposed in virtual reality. The pilot study was approved by the ethics committee of the University of Amsterdam (Approval number: 2014-CP-3660).

5.4.1. SUBJECTS

The pilot study was conducted with five social phobia patients who met DSM-IV [2] criteria for generalized Social Anxiety Disorder. The patients first filled in several questionnaires on psychopathology and were then interviewed with Structured Clinical Interview for DSM-IV (SCID-I, SCID-II/ avoidant PD). The sample consisted of two males and three females with an age ranging from 38 to 64 years old ($M = 49$, $SD = 10.63$).

5.4.2. PROCEDURE AND APPARATUS

At the start of the pilot study, patients were invited to the clinic for an introduction meeting with the therapist. In the introduction meeting therapists explained the background of the study and how to utilize the related hardware and software involved. Furthermore they also demonstrated how to setup all devices. Using the therapist application, the therapist registered the patient on the server system. After the introduction, patient received a suitcase with all equipment and a manual that they brought home. Each patient was scheduled to receive 10 treatment sessions. From the 10 sessions planned, 8 sessions (sessions 2 to 9) included exposure in the virtual reality, while session 1 served as an introduction session and session 10 as a relapse prevention session. At the start of each session, the therapist called the patient by phone. During the session the therapist would listen and advice the patient over the phone while the patient was using the system at home.

5.4.3. MEASURES

SUD scores and average heart rate were recorded every four minutes during VR exposure. The level of presence in the virtual reality during the first two treatment sessions was measured using Igroup Presence Questionnaire (IPQ) [21].

5.4.4. RESULTS

Due to technical glitches that arose unexpectedly during treatment sessions, only one patient, who used the same hardware set that was used in the usability test, was able to complete all 10 sessions successfully. For the other four patients, who used another brand of laptop, it was decided to stop the trial and offer them face-to-face treatment. This meant that for one patient data was collected from only the first six sessions, from two patients from only the first three sessions, and from one patient only the first two sessions.

The experiment data and R-scripts were available at 4TU Centre for Research Data*. The overall IPQ results were compared with online IPQ dataset (downloaded on March 2nd, 2015, at http://www.igroup.org/pq/ipq/data.php) for stereo HMD visual stimuli. The overall IPQ rating ($N = 5$, $M = 60.4$, $SD = 4.51$) was significantly higher ($t(21.83) = -7.36$, $p. < 0.001$) than the overall rating of the online IPQ dataset ($N = 37$, $M = 36.15$, SD

*doi:10.4121/uuid:7b156353-31a5-4935-ab87-da98dee36717

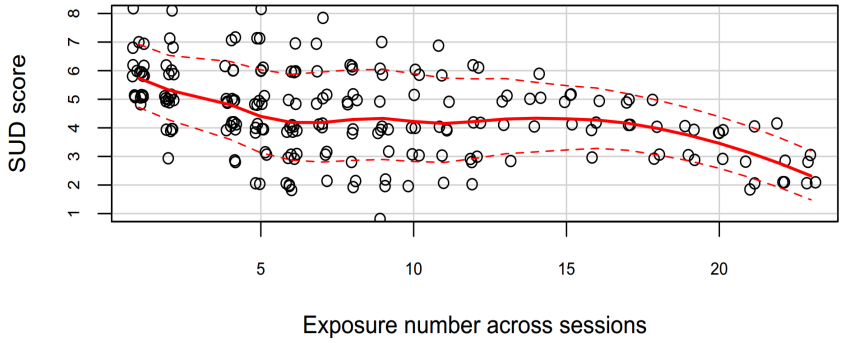

Figure 5.4: Self-report anxiety across the treatment sessions including .25 and .75 quantiles spread

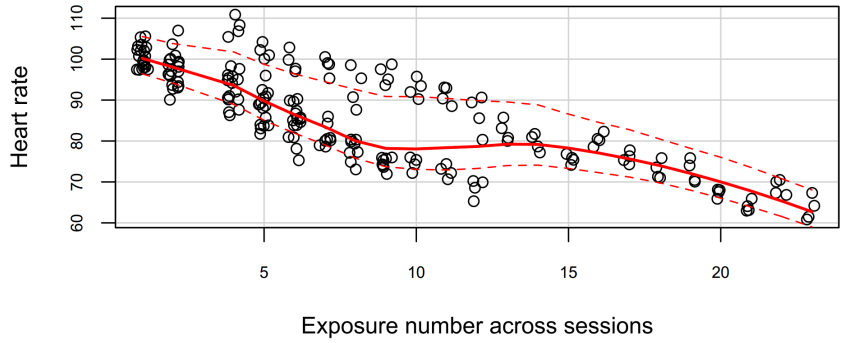

Figure 5.5: Self-report anxiety across the treatment sessions including .25 and .75 quantiles spread

= 15.87). The system therefore seems to have been successful in establishing significant levels of presence.

A total of 204 SUD scores were collected from the five patients. This data was analyzed with linear mixed-effect models (*lme*) in R taking the SUD scores as response variable and session number (2-9) and order number of the exposure exercise in a session (1-3) as factors nested within random effect variable participant. The objective of the analysis was not to generalize findings to a larger population, but instead to examine how SUD progressed for this sample, which for session 7 to 9 only included data from a single patient. The analysis showed that sessions ($\chi^2(1) = 24.2$, $p. < 0.001$) and exposure order number ($\chi^2(1) = 11.5$, $p. < 0.001$) had a significant effect on the SUD scores. No interaction effect between these two factors was found ($\chi^2(1) = 2.9$, $p. = 0.089$). As Figure 5.4 shows, patients self-reported anxiety level decreased over the 22 (8 session x 3 exercises – 2 as first and last session only included 2 exercises) exposures exercises.

Similar models were fitted on heart rate data ($n = 204$). Both session ($\chi^2(1) = 37.0$, $p. < 0.001$) and exposure order number ($\chi^2(1) = 71.5$, $p. < 0.001$) had significant effect on the heart rate data. Again no significant ($\chi^2(1) = 0.3$, $p. = 0.62$) two-way interaction was found. As Figure 5.5 shows also heart rate decreased over 22 exposure exercises.

5.5. CONCLUSION AND DISCUSSION

THE pilot study findings show that for this sample (1) the system could evoke anxiety and (2) over time the expected habituation sets in as anxiety levels dropped. Furthermore, the patients reported to have experienced a substantial level of presence, which is encouraging given that the 18 minutes dialogues were fully automated without intervention of a human to control the virtual characters. The pilot study also revealed a number of serious technical problems. These technical problems need first to be addressed before any further studies with patients can be considered. On the other hand, one patient, who used the non-failing equipment, was capable to complete all 10 of the home sessions, illustrating the system feasibility in treating patients if technical and usability problems are resolved. The technical problems included unexpected software crashes, but also patients forgetting to charge batteries of the mouse, and wireless hear rate device, but also problems getting the HMD to function properly, or simply finding or daring to click on a button. The later is interesting, as it shows that usability issues might be especially important for this user group to address. Apart from the described technological problems, the study has the following limitations. First, although a key step, this represent a pilot study with only a small sample and without a control condition to compare the findings with. Second, because of the technical glitch, patients did not do the exercise completely on their own. Often the therapist also had to provide technical support on the phone. Third, because of ethics considerations it was necessary at this stage to have a therapist listening in over the phone while patients conducted their exercises at home. Besides the insights the pilot study offered into the feasibility of home-based VRET, the scientific contribution of the work presented in this paper lies in the techniques proposed to address three key challenges, namely, (1) techniques a virtual health agent could apply to motivate a patient, (2) dialogue techniques to create 18 minutes long conversation with virtual characters, and (3) an automatic feedback loop to control the anxiety of a phobic patient. These contributions are not limited to the psychotherapy domain, but might also be beneficial for application domains that require a level of controlled stress in the form of conversation such as serious gaming or as part of stress test, for example Trier Social Stress Test.

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6

Discussion and Conclusions

THIS dissertation aimed to propose, develop and evaluate solutions for technological challenges in the context of a home-based virtual reality exposure therapy system to treat patients with social anxiety disorder. The study was designed to answer the following main research question:

> *How to provide virtual reality exposure therapy for social phobia patients at home?*

Three research hypotheses were derived from the main research question:

> **H1:** *The timing mechanism for obtaining self-reported anxiety experienced during exposure in virtual reality affects an individual's experience of a dialogue with a virtual human.*
>
> **H2:** *The ratio of positive and negative responses from a virtual human in a dialogue with individuals correlates proportionally with the individual's anxiety.*
>
> **H3:** *An individual's social anxiety in virtual reality can be regulated automatically.*

These hypotheses provide the foundation of the envisioned home-based virtual reality exposure therapy system for anxiety disorder treatment. Since this study also took the next step by implementing the proposed design, it was possible to address the following additional research question:

> *What is a feasible home-based virtual reality exposure therapy system for social anxiety disorder?*

The results presented in this thesis demonstrate that it is indeed possible to measure the level of anxiety automatically, to establish stimuli that can elicit different level of anxiety, and to regulate the patient's level of anxiety automatically during the exposure in virtual reality. These findings provide the building blocks of an automatic virtual reality exposure therapy system, which can be deployed at home and can be utilized by patients without the need for direct control by a therapist. As an answer to the main research question the research outcomes show how a virtual reality exposure therapy for social phobia patients can be provided at home.

The ***"how?"*** part of the main research question focused on the three main hypotheses and feasibility research question. Therefore, the conclusions of this dissertation can be structured by summarizing the arguments and justifications for these three hypotheses and the feasibility question.

The first hypothesis: *The timing mechanism for measuring self-reported anxiety affects the individual's experience.*
Support for the first hypothesis was established by conducting an empirical experiment to investigate the effects of different automatic self-reported anxiety timing mechanisms. A group of 24 non-patient participants were recruited and asked to give three different topic presentations in front of a virtual audience. The presentation lasted around three

minutes, after which the virtual audience started a questions and answers round. In each presentation session, the system used a different timing mechanism to ask participants to rate their level of anxiety. These timing mechanisms were: (1) dialogue-dependent (i.e. naturally in the flow of the dialogue), (2) speech-dependent (i.e. when both the user and the virtual human were silent), and (3) context-independent (i.e. at random times). The results showed that the automatic self-reported anxiety timing mechanisms affected participants' subjective experience and their behaviour in a dialogue-based virtual world. Furthermore, the participants rated the dialogue-dependent timing mechanism as less interruptive than the speech-dependent timing mechanism, which was again rated as less interruptive than the context-independent timing mechanism. This result shows the need for an accurate automatic self-reported anxiety timing mechanism as it could affect people's experience of a dialogue with a virtual human.

The second hypothesis: *The scenario characteristics and the ratio of positive and negative responses from a virtual human correlates with individual's anxiety.*

Support for the second hypothesis was established through two successive empirical studies. The first study investigated whether exposure to various social virtual scenarios is associated with different levels of anxiety. For this study 24 non-patient participants were recruited. All participants were exposed to a free-speech dialogue interaction with a virtual character in a blind date and job interview setting. The order of these two social interactions was counter balanced. As a baseline measurement, all participants were exposed to a neutral virtual world that created a non-anxiety evoking situation by watching a documentary about mountain animals on a television screen. The results showed that the participants' level of anxiety increased significantly between neutral world, the blind date, and the job interview. This indicates that various virtual social scenarios can evoke different levels of anxiety.

The second study was conducted to investigate the association between the ratio of negative and positive dialogue feedback responses made by a virtual character and an individual's level of anxiety. A new group of 24 non-patient participants was recruited for this study. All participants were exposed into two different experimental conditions: a positive virtual job interview condition and a negative virtual job interview condition. The order of both positive and negative virtual job interview conditions were counterbalanced. This second study is very similar in setup as the first study, with the distinction of the variation in the dialogue contents, i.e. a positive and negative style. With the positive dialogue style, the number of positive responses increased and negative responses decreased over time. With the negative dialogue style the reversed happened. Throughout the dialogue participants were asked to rate their anxiety level, while their heart rate as well as their speech behaviour were recorded. The analysis of the data showed that the manipulation of the dialogue style had a significant effect on people's level of anxiety, their attitude, their speech behaviour, their dialogue experiences, their own emotion and how they perceived the emotion of the virtual human. More specifically, the correlations between on the one hand the dialogue stressor ratio and on the other hand the means of SUD score, heart rate and audio length of participants' responses showed strong relationships. While positive dialogue feedback from the virtual character resulted in lower self-reported anxiety, lower heart rate, and longer answers; negative dialogue feedback

resulted in the opposite. Another interesting finding was that the level of anxiety could be influenced and controlled dynamically. This means that anxiety could not only be increased or decreased to a maximum or a minimum level, but this can also be reversed halfway. All these findings demonstrate that social dialogues in a virtual environment can be effectively manipulated for therapeutic purposes.

The third hypothesis: *An individual's social anxiety in virtual reality can be regulated automatically.*
The third hypothesis was also tested in an empirical study by examining the ability and effectiveness of an automatic feedback-loop regulation mechanism to maintain an individual's anxiety at a predefined target level when exposed to a virtual dialogue scenario that includes a set of stressors, i.e. dialogue style, eye gaze and body posture of the virtual human. For this study a group of 24 non-patient participants were recruited. They were exposed to two different system response conditions: a static and a dynamic condition. In the static condition participants were exposed to a static set of virtual reality stressors, which meant that during the exposure all stressors remained on the same anxiety provoking level (i.e. at 70% of their capacity) and never changed. In the dynamic condition participants were exposed to a set of virtual reality stressors that changed dynamically, aimed at keeping the anxiety of the participants at a stable level (e.g. 70% points on a personalised anxiety measure). The results showed that participants' level of anxiety could be regulated. The findings show that during the exposure in the static condition, in which there was no anxiety regulation, anxiety dropped as indicated by lower self-reported anxiety, lower heart rate, increasing heart rate variability, and longer answers. Conversely, during the exposure in the dynamic condition, where the automatic feedback-loop regulation mechanism was incorporated into the system, participants' anxiety levels were maintained around a pre-set anxiety reference value of 70%. On average, the anxiety measured deviated by only 9.7% from this pre-defined anxiety reference value. The overall findings therefore suggest that individuals' level of anxiety can be regulated automatically using an automatic feedback-loop mechanism.

The research question: *What is the feasibility of a home-based VRET system for social phobia patients?*
The feasibility research question was addressed by actually developing a home-based VRET system and empirically evaluating this system in a small pilot study. This home-based VRET system incorporated three key elements: (1) the dialogue techniques to create a free-speech dialogue interaction between virtual characters and patients in virtual reality worlds, (2) a multi-modal automatic anxiety feedback-loop mechanism to regulate patients' anxiety levels, and (3) motivational techniques applied by the virtual health agent. To evaluate the system, a group of five social anxiety disorder patients were recruited to participate in a pilot study. During the study, all patients received a complete VRET hardware system set and completed the treatment at home with minimal support from the therapist. All patients were scheduled to have 10 treatment sessions. The findings show that the system could evoke anxiety, which dropped over time as patients' self-reported anxiety and heart rate gradually decreased during the exposure sessions. Furthermore, all patients reported experiencing a substantial level of presence, which is encouraging given that the 18-minute long dialogues with the virtual human were fully

automated using speech recognition technology. These findings suggest that delivering a home-based VRET system is feasible.

6.1. LIMITATIONS

DESPITE encouraging empirical evidence and the promising results, to further appreciate the study's findings it is also important to reflect on its limitations. *First*, although this research focused on developing a home-based virtual reality exposure therapy system to treat patients with social anxiety disorder, most participants included in this study were not diagnosed with a social anxiety disorder. Only a small number of 5 patients met the DSM-IV [1] criteria for generalized social anxiety disorder, i.e., the participants in the pilot study of chapter 5. Individuals with a social anxiety disorder tend to have a stronger reaction and are more sensitive to phobic stressors in virtual reality such as eye gaze (direction), eye blink rate and hyper-scanning, as well as tend to have more positive and negative attitudes towards them [2,3]. However, if anxiety is considered on a continuous scale, the difference found between lower and higher anxiety of non-patients in this thesis and other studies [4-6] might also be generalised to patients (i.e., individuals higher up on the social anxiety scale). Still, despite the promising results, further research with a larger number of social anxiety disorder patients is needed before strong generalizations can be made towards this population.

Second, this study focused heavily on the development of a system for social anxiety disorder treatment. Therefore, the scope of benefits and contributions mainly generalize to the mentioned domain. However, the available (fear) exposure elements and stimuli that were incorporated in the system, such as the dialogue stressor and behavioral stressor elements of the virtual characters, could potentially be applied in other application domains, such as serious gaming [7], psychological stress testing [8,9], studying paranoia [10] [11], and negotiation simulation [12].

Third, although after the exposure sessions multi-dimensional emotion measures were used, e.g. SAM [13], during the exposures, the measures mainly captured anxiety. Still, insight into experiences of other emotions, such as being hurt during virtual exposure, could have therapeutic value. Therefore, future research should also consider using multi-dimensional emotion measures [14,15] during virtual reality exposure to enhance the understanding of the psychological experiences.

Fourth, the development of the home-based VRET system in this study was heavily based on the current state of existing technology, with its associated level of usability and reliability (e.g. the physiological sensory devices, the speech recognition software, computing power, and the head mounted display). However, with the vast and rapid development of hardware and software technology in this area, in the future, these currently constraining technological factors might be overcome, making this home-based VRET system even more feasible.

6.2. CONTRIBUTIONS

6.2.1. SCIENTIFIC CONTRIBUTIONS

FOUR main scientific contributions can be identified in the work presented in this thesis. *First* is the understanding gained about the effect on people's experience and

behaviour by the type of automatic timing mechanism to measure subjective levels of anxiety when people are engaged in a dialogue with a virtual human. This timing mechanism seems to be an important element that needs to be considered delicately since, in the context of virtual reality, any interruption could mean a break in presence [16,17] where individuals stop responding to the virtual environment and start shifting their reaction to the real word instead. Moreover, keeping the individual's level of presence uninterrupted is important since this has also been associated with self-reported anxiety [18].

Second, valuable insight has been gained about the dialogue stressor that can be utilized to elicit and induce different levels of anxiety in the dialogue-based virtual reality exposure therapy. This was done by manipulating the ratio of the dialogue polarity (i.e. positive and negative style of the dialogues). Furthermore, to the best of our knowledge, the dialogue produced and applied in this automatic virtual reality exposure system is the most extensive existing at this time. The ability of such a system to engage people in relatively long conversations with a virtual human was demonstrated in several of the studies presented in the thesis. Besides the psychotherapy domain, this could be beneficial for other domain applications as well, for example Trier Social Stress Test training [19], job interview training [4], presentation training [20], or serious gaming [21] since in all these domains an individual could benefit from a conversation that could elicit different levels of anxiety.

In recent developments of virtual reality exposure therapy systems, therapists are heavily involved during the exposure session by manually adjusting the anxiety evoking stimuli to elicit the required anxiety responses from the patients. To provide a home-based virtual reality exposure therapy system that requires less involvement from a therapist, an automatic mechanism to regulate the patient's level of anxiety is preferred. *The third* scientific contribution of this study lies in the development and validation of such a mechanism as a feedback-loop algorithm to regulate a patient's level of anxiety automatically. This negative feedback-loop algorithm regulates the patients' anxiety by monitoring their anxiety levels and automatically adjusting the phobic stressors in the virtual social scenario in real-time fashion, reaching the desired level set by the therapist prior to the exposure session. To monitor patients' level of anxiety, the thesis presents an algorithm that combined both automatic self-reported anxiety using speech recognition technology [22] and a heart rate measurement device into a single anxiety measure. Furthermore, the thesis shows how both measurements can be personalised at runtime to cope with individual variations in expressing anxiety.

The last key scientific contribution this thesis put forward is the blueprint for the design of a home-based virtual reality exposure therapy system where patients with social phobia are treated and supported by a virtual health agent. The blueprint incorporated three key techniques that might be beneficial for psychotherapy and other application-related domains. They are: (1) dialogue techniques to establish automated free-speech dialogue interactions between an individual and a virtual human in the virtual reality world, (2) an automatic multi-modal anxiety feedback-loop mechanism to control and regulate levels of anxiety automatically, and (3) motivational techniques incorporated in a virtual health agent to support and motivate patients during the treatment sessions. The system's blueprint, when implemented, seems to be able to provide a substantial

level of presence, and elicit the required anxiety in patients suffering from a social anxiety disorder.

6.2.2. PRACTICAL CONTRIBUTIONS

THE main practical contributions of the work presented in this thesis can be summarised as the insight gained on how and what needs to be considered and established in the development of an (semi) autonomous virtual reality exposure therapy system, especially for home-based use to treat people with social anxiety disorder with limited need for direct therapist involvement. These contributions can be classified according to the various beneficiaries, such as patients, clinical researchers, therapists, and application developers.

PATIENTS

The gold standard for treating patients with social anxiety disorder is in vivo exposure, where patients are gradually exposed to anxiety provoking stimuli for prolonged periods until habituation occurs and their anxiety dissipates [23]. A classical problem with in vivo exposure is the difficulty of building up a gradual anxiety hierarchy to be used during the treatment, as other people or environments that act as stressor stimuli in the real world have unpredictable reactions and responses. Furthermore, the social interactions offered are time-limited, generally not long enough for habituation to occur. Moreover, since not all patients are ready to be exposed to the dreaded and daunting real-life social environments that they fear, the reported refusal and dropout rates during treatment are considerably high [24-27]. And finally, the lack of trained therapists leads to a long waiting list for patients to get the treatment, and, in rural areas, access to face-to-face meetings or therapy are limited [28].

This thesis outcome is the blueprint for a home-based virtual reality exposure therapy system, when implemented referred to as the Memphis system [29,30]. It is a system for home use, in which patients with social anxiety disorder can be treated using (semi) autonomous virtual reality exposure that is supported by a virtual health agent, aiming for a minimum need for direct therapist intervention. Moreover, since it is a home-based VRET system, it provides an opportunity to be flexible in terms of use, as patients can use it independent of time and place. This system provides an alternative to overcome the shortcomings of in vivo exposure by providing a safe environment where patients can get exposure in a controlled way.

CLINICAL RESEARCHERS

The blueprint can also be beneficial for clinical researchers as a platform for their clinical experiments, because it provides them a highly controllable environment. It provides the opportunity of controlling different aspects of exposure elements gradually, such as dialogue styles [4], eye gaze [29-31], posture, attitude and facial expressions [29-31]. It also offers the ability for experimenters to externally regulate anxiety levels of an individual. In addition, it opens the door for studying remote treatment delivery. It provides an opportunity to shift away from the traditional clinic-centred treatment to a more flexible (remote) treatment, making it more accessible for patients.

THERAPISTS

The system presented in this thesis can help therapists to deliver their treatment remotely, including monitoring patient progress, but also personalising it by creating a treatment plan. This approach might not only help to reduce the use of very intensive mental healthcare services and therapist workload, but also reduces the barrier for the patients to seek professional help [32].

APPLICATION DEVELOPERS

This thesis work also has some implications for application developers, especially in the virtual reality related domain. This thesis provides a blueprint for a home-based virtual reality exposure therapy system. The blueprint of the Memphis system includes: (1) an automatic mechanism to measure patients' level of anxiety using self-reported SUD score combined with speech recognition technology; (2) a procedure to elicit and control anxiety evoking stimuli; and (3) a multi-modal and autonomous anxiety regulation system. Furthermore, the blueprint also has a number of other important elements that might be useful for application developers such as the design and implementation of various virtual social scenes, the virtual health agent, the therapist application and a secure remote database server. The blueprint can also be useful when considering developing systems for other domains that include dialogues with virtual characters or that focus on eliciting anxiety, such as psychological stress testing [19], negotiation simulation [12], presentation training [20], job interview training [4], or serious gaming in general [21].

6.3. FUTURE RESEARCH

THE research described in this thesis can be further improved and extended in several ways. Hence, suggestions are provided for future research directions, especially in the virtual reality exposure therapy and related topics domain. *First*, the remote VRET system described in this thesis was studied in a small pilot study with patients. More research is needed to study the acceptance level, usability, and effectiveness of such a system. Besides a larger sample group, it would also be interesting to compare therapy delivered in this way with existing treatments.

Second, the remote VRET system with its virtual health agents presented in this thesis mainly supported behavioural therapy, specifically exposure therapy. Although the virtual health agents provide psycho-education, future research might consider extending the system to support other elements of cognitive therapy such as cognitive restructuring, behavioral strategies, interoceptive exposure and necessary social skill training [33,34]. Offering both cognitive and behavioural therapy remotely with limited need for direct therapist involvement would be interesting, especially as Anderson et al. [35] found that virtual exposure therapy combined with cognitive therapy is equally effective as in vivo exposure therapy combined with cognitive therapy when offered in the clinic. Furthermore, several studies [36-39] demonstrated that remote cognitive therapy can be offered and delivered remotely via the internet. However, the technical support of cognitive therapy is often limited to paper-based self-help websites, ongoing support using email, online questionnaires, online messenger services and real-time audio and video teleconferencing. Further work might therefore look into different types of remote

therapy interaction, especially by offering an intelligent virtual agent to guide and accompany the patient during the treatments. Based on the information collected from the patient, such an agent can tailor the treatment to patients' needs, thereby reducing the therapist's workload.

Third, the system studied in this thesis included a number of social stressors. Having a larger set of stressors makes it possible to cater for specific individual social anxieties. Therefore, future work might examine new social stressors that could be incorporated into a virtual environment; examples include emotions of facial expressions during interpersonal communication [40], different age [41], gender, cultural and ethnic groups [42], masculinity and femininity [43] or techniques to interrupt the patients when they are talking too long during the conversation as part of their avoidance behaviour [44].

Another research direction would be to enhance the level of interactivity of the system. Currently the system relied heavily on speech recognition technology as the hub of natural dialogue engagement between patient and virtual character. Furthermore, the system responded to individual anxiety levels by adjusting stressors based on biofeedback (i.e. heart rate) and self-reported anxiety measurements. The interactivity might, for example, be enhanced by detecting and reacting to people's focus of attention in the virtual world [45]. This direction of the user's gaze and the duration of the fixation [46,47] could be an indicator for people's focus of attention. A simple implementation of this idea could be to adjust the virtual characters' behaviour depending whether or not the person is looking at them when giving a presentation in front of a virtual audience. Also enhancing the variation in the virtual characters' facial expression, for example by expressing blended emotions, could improve the natural engagement and enrich the experiences inside the virtual reality environment.

Accordingly, in this thesis, the major scope of the work is exploring the upper body emotion expression that can affect human emotion, behaviour, perception, attitude and beliefs. Further research suggests it might be beneficial to consider, explore and implement a full body emotion expression in a dialogue-based virtual reality exposure therapy system. Several studies [48-50] already indicate promising results that full body emotion expression does indeed play an important role in the perception and expression of emotion or attitude.

Fourth, the work can be extended to explore if the proposed blueprint for treatment of social anxiety disorder can be used for other mental health disorders. A potential candidate would be psychotic disorders [51,52], especially as exposure to social interaction could be therapeutically beneficial. Other applications would be to focus especially on social skills training as part training of Tier Social Stress Test, job interview and presentation training, negotiation simulation or even serious gaming.

6.4. FINAL REMARKS

SOCIAL anxiety disorder is one of the most frequently occurring types of mental disorder. In the Netherlands alone, it estimated to affect around a million people during their lifetime and nearly half a million at any one time within the age range of 20-65 years. The main objective of this thesis was therefore to propose, develop and evaluate solutions for technological challenges in the context of a home-based virtual reality exposure therapy system to treat patients with social anxiety disorder. Three main em-

pirical studies were conducted followed by a feasibility study to evaluate the proposed system design. The results showed that the automatic self-reported timing mechanism does indeed affect people's subjective experiences and their behaviour in a dialogue-based virtual world. This, therefore suggests that the need for an accurate automatic timing mechanism is important as it could affect the efficacy and effectiveness of the proposed system. Another important element to be considered is how to elicit different levels of anxiety during the exposure therapy. This can be achieved by developing various virtual social scenarios, derived from the common social situations that are often used during the CBT treatment. Furthermore, in the dialogue based VRET system, the dialogue elements also play a major role to evoke different level of anxiety. By manipulating the ratio of positive versus negative dialogue comments made by virtual characters it is possible to control people's anxiety and speech behaviour. Another important finding was that people's level of anxiety could be influenced and controlled dynamically. This demonstrate that social dialogue in virtual reality could be used for therapeutic purposes effectively. People's level of anxiety can not only be influenced and controlled dynamically, but can also be regulated automatically. It can be regulated automatically using an automatic feedback-loop mechanism.

In short, this study demonstrates that the proposed and designed VRET system could evoke the required anxiety in patients with a substantial level of presence. This finding suggests that delivering a home-based VRET system is indeed possible. It offers both patients and therapists numerous benefits. Even though the results are promising, further research to examine the usability, acceptance and effectiveness of this home-based VRET system is recommended.

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Dwi Hartanto,
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APPENDIX A

A typical dialogue interaction between a participant (P) and an avatar (A) as observed in the experiment (this dialogue conversation example was performed by a non-native English speaker participant):

(100%) Positive dialogue style ratio:

A question: *"Why do you want to work for our company?"*
P: *"Because it matches with my expertise and my passion for sure."*
A response: *"A very good reason indeed! I can see and feel a lot of passion in you now!"*
A question: *"What do you know about our company?"*
P: *"This company has many brilliant products, from internet service until advanced mobile operating systems, that's why I would love to work here if I can get hired. Because this what I'm good at!"*
A response: *"Well... very good! It seems that you know a lot about this company!"*
A question: *"What is your management experience?"*
P: *"My previous job was a team leader in a start-up software company, so I have experience in developing high demand software and at the same time maintained my team work that consist of number of software engineers."*
A response: *"You have that experience? That's a very good experience!"*
A question: *"What are you most proud of?"*
P: *"Hmmm...* [thinking] *when I get my master degree with a honour."*
A response: *"That's a very good achievement indeed! I am really impressed!"*
A question: *"What is the biggest mistake that you have ever made?"*
P: *"Emm...* [thinking] *maybe when I didn't learn a Java language at the first priority. I was a bit sceptics about java at that time and more focused on WPF instead. Then Android came and turned around the table, where java is a must. Well, now I'm a big fan of Android operating system. So, the only thing to catch is I need to learn java, bit by bit. But finally I can catch the learning process in the end. However, I've just regretted and imagine if I'm not that late to learn java. But you know, now I'm not that bad after all* [chuckle], *but yeah just regret it. A bit."*
A response: *"Interesting! So you have learned a lot starting from that moment then."*
A question: *"How do you handle stress?"*
P: *"Em...* [thinking] *Well, sure! I have a good self-management and well organize person. I keep track on every task and trying to deliver it as soon as possible. So, with this approach I can prevent myself from deadline pressure and stress over my work. And I'm glad it still works until now!"*
A response: *"Hmmm...* [amazed tone] *A very good approach indeed! I'm so impressed!"*
A question: *"Tell me about your hobbies please?"*
P: *"Well, I like photography. So, normally during the weekend or holiday, I go out and try*

to start capturing a nice object or rare moments wherever I go. And this hobby sometimes give you money [chuckle], *of course by selling it to the newspaper agency. Or you can share it to the world and let other people enjoy the beauty that you'd just captured. And when a lot of people like it, that's another priceless moment that you can enjoy."*
A response: *"A very interesting hobby indeed! A really nice one!"*

(100%) Negative dialogue style ratio:

A question: *"Are you sure you want to work for our company?"*
P: *"Yes, I like this company."*
A response: *"That's all? Nothing else? It seems you're not so serious about working here!"*
A question: *"Are you sure you know something about this company?"*
P: *"Hmmm yes, more less. Your search engine is world famous."*
A response: *"Hmm...* [doubting tone] *You should have at least visited our website before coming here!"*
A question: *"I don't think that you have management experience, do you? Or am I wrong?"*
P: *"Mmm...* [thinking] *I have for sure, when I was in internship, I have a role to take on some of software development modules. My supervisor promoted me to be the organizer, so one of my task was organizing the software release together with couple of my colleagues. I manage to deliver the package modules on time and keep my team in a good shape."*
A response: *"Oh, well, it seems that you have nothing there then!"*
A question: *"I'm sure that you have nothing to show, but in case I'm wrong, can you tell me what you are most proud of?"*
P: *"Mmm...* [thinking] *Maybe when I won a national software competition while I'm still in my bachelor."*
A response: *"That's all? Doesn't look so good to me. But never mind, let's continue!"*
A question: *"I assume that you have made a lot of mistakes in the past, can you tell me the biggest one?"*
P: *"Well, Mmmm... [thinking] Maybe when I lost my project documents when there's an option to make a backup regularly. I was thinking that I don't have so much time to do a backup at that time, so I just keep ignoring the pop up message. Until there's a hardware failure and wipe away my documents."*
A response: *"That's a stupid one! Around here we don't tolerate this kind of mistakes!"*
A question: *"Hmmm...* [doubting tone] *Can you handle stress? And how?"*
P: *"Mmm...* [thinking] *I think simply by avoiding it. You need to have a good time management to do this."*
A response: *"Hmm...* [doubting tone] *That's all? That's doesn't look so good to me!"*
A question: *"Do you have any hobbies?"*
P: *"Yes. I like doing sport exercise, especially jogging or running. And every weekend I spend a couple of hours jogging just to keep myself always in a good shape."*
A response: *"Hmm... Typical!* [long breath taking] *yeah, most of people will answer that!"*

APPENDIX B

Erratum:
Hartanto, D., Kang, N., Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G M., Neerincx, M., 2012, *Automatic Mechanisms for Measuring Subjective Unit of Discomfort,* Annual Review of Cybertherapy and Telemedicine.

Page 195:
Table 2: Mean, Median (IQR) and Inter-observer agreement of the relative frequency for five dialog replies in three conditions. Should read:

Table 2: Mean, Median (IQR) and Interobserver agreement of the relative frequency for five dialog replies in three conditions.

Measure	Dialog Dependent	Speech Dependent	Context Independent	Interobserver agreement (*r*)
Details answer	0.31, 0.23 (0.43)	0.23, 0.17 (0.23)	0.18, 0.18 (0.29)	0.72 – 0.88
Normal answer*	0.40, 0.31 (0.55)	0.31, 0.29 (0.52)	0.29, 0.23 (0.43)	0.81 – 0.91
Simple/ short answer	0.23, 0.16 (0.26)	0.30, 0.28 (0.43)	0.21, 0.23 (0.18)	0.75 – 0.84
"Don't know" answer	0.06, 0.00 (0.00)	0.16, 0.00 (0.25)	0.16, 0.00 (0.29)	0.93 – 0.98
"Lost in the dialog" **	0.00, 0.00 (0.00)	0.00, 0.00 (0.00)	0.16, 0.00 (0.27)	0.95 – 0.98

* $p < 0.05$; ** $p < 0.001$

Page 195: paragraph 2, the fourth line should read: no significant effect was found for the timing mechanism on participants' replies in the detail answer, simple/ short answer and *"don't know"* answer measures.

Page 195: paragraph 2, the fifth line should read: a significant effect was found in the normal answer ($\chi^2(2) = 6.20$, $p = 0.045$).

Page 195: paragraph 2, the eighth line should read: in the *"normal answer"*, only a difference between dialog dependent and context independent (Z = -1.89, $p = 0.059$) timing mechanism was found that approached the significant level of 0.05.

Page 195, paragraph 2, the 12th line should read: (Z = -2.95, $p = 0.003$).
Page 195, paragraph 2, the 13th line should read: (Z = -2.95, $p = 0.003$).

APPENDIX C

Erratum:
Hartanto, D., Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., Neerincx, M.A., Brinkman, W-P. (2014). *Controlling Social Stress in Virtual Reality Environments*, PLoS ONE 9(3): e92804.

Abstract:
Page 1: paragraph 1, the 12th line should read: $r(6) = 0.90$, $p = 0.002$; $r(6) = 0.74$, $p = 0.036$ and $r(6) = -0.91$, $p = 0.002$ respectively.

Page 4: Table 1, should read:
SUD score (0-10):
Blind date – Job interview: $p = 0.011$.
Heart rate (bpm):
Neutral – Blind date: *M2*(*SD*) = 81.2 (11.30).
Neutral – Job interview: *M2*(*SD*) = 84.1 (11.03).
Blind date – Job interview: *M1*(*SD*) = 81.2 (11.03), *M2*(*SD*) = 84.1 (11.03), $p = 0.048$.

Page 7: column 1, paragraph 3, the eighth line should read: ($t(40.98) = -4.64$, $p < 0.001$).
Page 7: column 2, paragraph 1, the first line should read: ($M = 38.93$, $SD = 17.09$).
Page 7: column 2, paragraph 2, the seventh line should read: ($F(4,12) = 19.14$, $p < 0.001$, $\eta^2 = 0.87$).
Page 7: column 2, paragraph 2, the ninth line should read: ($F(2,30) = 23.08$, $p < 0.001$, $\eta^2 = 0.61$).
Page 12: column 2, paragraph 1, the fourth line should read: ($M = 29.38$, $SD = 3.28$).
Page 14: column 1, paragraph 3, the fourth line should read: ($M = 25.0$, $SD = 12.6$).
Page 6: Table 2, should read:
SUD score (0-10):
Dialogue stressors: $F(3.66, 80.60) = 27.66$, $p < 0.001$, $\eta^2 = 0.56$.
Social anxiety group (high and low): $F(1, 22) = 6.84$, $p = 0.016$, $\eta^2 = 0.24$.
Dialogue stressor x Social anxiety group: $F(3.66, 80.60) = 5.68$, $p < 0.001$, $\eta^2 = 0.21$.
Page 9: Table 4, should read:
Valence:
Dialogue stressors: $\eta^2 = 0.64$.
Dominance:
Dialogue stressors, $\eta^2 = 0.59$.
Page 14: column 1, paragraph 4, the seventh line should read: ($t(46.04) = 3.73$, $p < 0.001$).
Page 14: column 1, paragraph 4, the eighth line should read: ($M = 38.93$, $SD = 17.09$).
Page 14: column 1, paragraph 5, the eighth line should read: ($F(18,5) = 106.01$, $p < 0.001$, $\eta^2 = 1.00$).

Page 14: column 1, paragraph 6, the tenth line should read: $r(6) = 0.90$, $p = 0.002$; $r(6) = 0.74$, $p = 0.036$ and $r(6) = -0.91$, $p = 0.002$ respectively.
Page 14: column 1, paragraph 6, the tenth line should read: The result of the overall analysis also showed that there was no significant overall main effect for the higher and lower social anxiety groups, ($F(3,20) = 2.87$, $p = 0.062$, $\eta^2 = 0.30$). However,...
Page 7: Table 3, should read:
SUD score (0-10):

50% (end) – 0% (C4): $p = 0.006$.
0% - 25%: $p = 0.018$.
25% - 50% (avg): $p = > 0.999$.

Heart rate (bpm):

50% (end) – 0% (C4): $p = 0.984$.
0% - 25%: $p = 0.002$.
25% - 50% (avg): $p = 0.039$.
100% - 50% (end): $p = 0.998$.

Audio length (s):

50% (end) – 0% (C4): $M1(SD) = 134 (26.0)$.

Page 14: column 2, paragraph 2, the fourth line should read: ($F(18,5) = 2.34$, $p = 0.176$, $\eta^2 = 0.89$).
Page 14: column 2, paragraph 2, the 16th line should read: A similar pattern seems to appear in the heart rate at those two points in Figure 7, although not significant this time (100% negative dialogue style ratio: $t(22) = -1.78$, $p = 0.088$; 0% negative dialogue style ratio: $t(5.53) = -0.28$, $p = 0.79$).
Page 14: column 2, paragraph 5, the fourth line should read: As depicted in Figure 8, on the arousal dimension, the high social anxiety group reported significantly more ($t(5.47) = -2.71$, $p = 0.039$) arousal than the low social anxiety group in the positive condition, while no significant difference ($t(22) = 1.25$, $p = 0.22$) was found in the negative condition. Furthermore, for the dominance affective dimension, the higher social anxiety group felt significantly less ($t(22) = 2.98$, $p = 0.007$) dominant than the lower social anxiety group in the negative condition, while this time no significant difference ($t(22) = -0.20$, $p = 0.846$) was found in the positive condition. Finally for the valence dimension, the higher social anxiety group rated valence not significantly higher ($t(22) = -1.91$, $p = 0.069$) than the lower social anxiety group in the positive condition, and no significant difference ($t(5.82) = 1.55$, $p = 0.173$) was found in the negative condition between the two groups.
Page 15: column 1, paragraph 3, the seventh line should read: more ($t(22) = -3.67$, $p = 0.001$) valence.
Page 15: column 1, paragraph 3, the eighth line should read: ($t(22) = 1.78$, $p = 0.089$).
Page 15: column 1, paragraph 4, the second line should read: (DEQ: $M = 32.84$, $SD = 1.00$; IAQ: $M = 20.38$, $SD = 4.2$).
Page 15: column 1, paragraph 4, the fourth line should read: (DEQ: $M = 38.32$, $SD = 1.24$; IAQ: $M = 30.25$, $SD = 3.21$).
Page 15: column 1, paragraph 4, the 16th line should read: ($t(5.26) = 3.55$, $p = 0.015$).
Page 15: column 1, paragraph 4, the 18th line should read: ($t(5.57) = -1.85$, $p = 0.118$).

APPENDIX D

Erratum:
Hartanto, D., Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., Neerincx, M.A. (2016). *Home-Based Virtual Reality Exposure Therapy with Virtual Health Agent Support.* Pervasive Computing Paradigms for Mental Health. MindCare. Communications in Computer and Information Science, vol 604. Springer, Cham.

Page 95, paragraph 2, the third line should read: ($t(21.83) = -7.36$, $p. < 0.001$).
Page 95, paragraph 2, the fourth line should read: ($M = 36.15$, $SD = 15.87$).
Page 95, paragraph 3, the eighth line should read: ($\chi^2(1) = 11.5$, $p. < 0.001$).

CURRICULUM VITÆ

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EDUCATION

2001–2005 Bachelor of Science in Informatics Engineering
Institute of Science and Technology AKPRIND, Yogyakarta, Indonesië
Thesis: Developing Smart Fire Fighting Robot Based-on ANN (Artificial Neural Network) Intelligent Algorithm

2007–2009 Master of Science in Computer Engineering
Technische Universiteit Delft, Nederland
Thesis: Reliable Ground Segment Data Handling System for Delfi-n3Xt Satellite Mission

2011–2017 PhD. Computer Science
Technische Universiteit Delft, Nederland
Thesis: Computer-based Social Anxiety Regulation in Virtual Reality Exposure Therapy
Promotor: Prof. Dr. M. A. Neerincx
Copromotor: Dr. Ir. W. P. Brinkman

LIST OF PUBLICATIONS

■ Ready and plan to submit:

[11] **Hartanto, D.**, Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., Neerincx, M.A. *Computer-based Fear Regulation during Virtual Reality Exposure for Social Anxiety.*

■ 2016:

[10] **Hartanto, D.**, Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., Neerincx, M.A. (2016). *Home-Based Virtual Reality Exposure Therapy with Virtual Health Agent Support.* In: Serino S., Matic A., Giakoumis D., Lopez G., Cipresso P. (eds) Pervasive Computing Paradigms for Mental Health. MindCare. Communications in Computer and Information Science, vol 604. Springer, Cham. DOI:10.1007/978-3-319-32270-4_9.

[9] Kampmann, I.L., Emmelkamp, P.G.M., **Hartanto, D.**, Brinkman, W-P., Zijlstra, B.J., & Morina, N. (2016). *Exposure to virtual social interactions in the treatment of social anxiety disorder: A randomized controlled trial.* Journal Behaviour Research and Therapy, 77. DOI:10.1016/j.brat.2015.12.016.

■ 2015:

[8] **Hartanto, D.**, Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., & Neerincx, M.A. (2015). *Design and Implementation of Home-Based Virtual Reality Exposure Therapy System with a Virtual eCoach.* In Intelligent Virtual Agents (IVA). Springer International Publishing. DOI:10.1007/978-3-319-21996-7_31

[7] Morina, N., Brinkman, W-P., **Hartanto, D.**, Kampmann, I.L., & Emmelkamp, P.G.M. *Social interactions in virtual reality exposure therapy: A proof-of-concept pilot study.* (2015). Technology and Health Care. DOI: 10.3233/THC-151014.

■ 2014:

[6] **Hartanto, D.**, Kampmann, I.L., Morina, N., Emmelkamp, P.G.M., Neerincx, M.A., Brinkman, W-P. (2014). *Controlling Social Stress in Virtual Reality Environments*, PLoS ONE 9(3): e92804. DOI:10.1371/journal.pone.0092804.

[5] Morina, N., Brinkman, W-P., **Hartanto, D.**, Emmelkamp, P.M.G. 2014. *Sense of presence and anxiety during virtual social interactions between a human and virtual humans.* PeerJ, 2:e337. DOI:10.7717/peerj.337.

■ 2012:

[4] **Hartanto, D.**, Kang, N., Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.G M., Neerincx, M., 2012, *Automatic Mechanisms for Measuring Subjective Unit of Discomfort*, Annual Review of Cybertherapy and Telemedicine. DOI:10.3233/978-1-61499-121-2-192.

[3] Brinkman, W-P., **Hartanto, D.**, Kang, N., de Vliegher, D., Kampmann, I.L., Morina, N., Emmelkamp, P.M.G. 2012. *A virtual reality dialogue system for the treatment of social phobia.* CHI'12: human factors in computing systems.

[2] **Hartanto, D.**, Kang, N., Brinkman, W-P., Kampmann, I.L., Morina, N., Emmelkamp, P.M.G., Neerincx, M. 2012. *Measuring the Subjective Unit of Discomfort using Speech Technology.* Journal of CyberTherapy and Rehabilitation, 5(2). Extended abstract.

[1] Morina, N., Beuving, J., Deiman, A., Kampmann, I.L., Brinkman, W-P., **Hartanto, D.**, Emmelkamp, P.M.G. 2012. *Social Virtual Environments for the Treatment of Social Phobia: Using Different Virtual Reality Displays.* Journal of CyberTherapy and Rehabilitation, 5(2). Extended abstract.