UNIVERSITY OF SALFORD

PhD Thesis

Triggering and measuring neural response indicative of inhibition in humans during conversations with virtual humans

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Abbreviations

BOLD Blood Oxygen-Level Dependent

DLPFC Dorsolateral Prefrontal cortex

EEG Electroencephalography

fMRI Functional Magnetic Resonance Imaging

fNIRS Functional Near-Infrared Spectroscopy

HbO Oxygenated Haemoglobin

HbR Deoxygenated Haemoglobin

HbT Total Haemoglobin

HMD Head Mounted Display

IPT Immersive Projection Technology

MPFC Medial Prefrontal Cortex

PET Positron Emission Tomography

PFC Prefrontal Cortex

PTSD Post Traumatic Stress Disorder

SNR Signal to Noise Ratio

SPM Statistical Parametric Mapping

VH Virtual Humans

VR Virtual Reality

VRET Virtual Reality Exposure Therapy

Abstract

The aim of this PhD was to determine if a confrontational virtual human can evoke a response in the prefrontal cortex, indicative of inhibiting an antisocial response. It follows previous studies by Aleksandra Landowska (2018) and Schilbach (2016) demonstrating that a prefrontal cortex response indicative of inhibition can be evoked by a virtual environment. The test scenario was a conversation about BREXIT, the United Kingdom leaving the European Union. This was used in three experiments which varied in level of immersivity of the interface and iteratively tweaked methods. A virtual reality head-mounted display (HMD) was adopted in the first experiment, a 50-inch display monitor was adopted in the second experiment, while the third experiment was carried out in an immersive suite. The independent variable in the experiments was the friendliness of the virtual human confederates. fNIRS was used to measure changes in haemoglobin in the medial and dorsolateral prefrontal cortex. Video recordings were taken to capture possible behavioural evidence that may be associated with inhibition. The friendliness of the virtual human was measured using the likeability section of the Godspeed Questionnaire series. This may be the first study to use functional near infrared spectroscopy (fNIRS) to measure response to virtual humans; previous studies have used functional magnetic resonance imaging (fMRI), which provides a less natural experience and is not conducive to non-verbal communication. The results from the first experiment suggest an effect emanating from prior experience with VR and gaming. Consequently, participants were grouped into two, with G1 representing the group with prior VR and gaming experience and G2 representing the group with no VR and gaming experience. Increased activation was found in the dorsolateral prefrontal cortex (DLPFC) during conversation with the confrontational (unfriendly) virtual human confederate for G2, in line with similar studies of emotional regulation. G1, on the other hand, showed increased activation in the medial prefrontal cortex (MPFC) during the conversation with the friendly virtual human confederate. The second experiment which was aimed at validating the outcome of the first experiment also showed an effect emanating from prior experience with VR and gaming. The results suggest increased activation in the MPFC for G1 and increased activation in the MPFC and DLPFC for G2 during the conversation with the friendly virtual human confederate in both groups. The third experiment showed increased activation in the DLPFC during the conversation with the unfriendly virtual human confederate across participants. Furthermore, head-mounted displays complicated data capture with the fNIRS; a problem alleviated by screen or projection-based approaches. Although all the experiments in this research targeted healthy subjects, the

outcome may be of interest to health professionals and technology providers interested in mental deficits relating to antisocial behaviours. It also finds potential application in mental health illness such as PTSD and autism where inhibitory responses are impaired

CHAPTER 1

INTRODUCTION

1.1 Background

As a crucial part of our daily activity in life, we engage in social interaction with people (So, Wong, & Lam, 2016). In the course of social interaction, the exhibition of aggression and anti-social behaviour is common (Bruijnes, Linssen., Akker, Theune., Wapperom, Broekema & Heylen, 2015; Song, Volling, Lane, & Wellman, 2016). However, the degree of exhibition of these varies across individuals. While some individuals appear visibly expressive, others do not (Blair, 2001; Smith, Pepler, & Rigby, 2004). Several factors account for aggression and anti-social behaviour during interaction. Some of these factors are lesions in the brain (especially regions implicated during executive functioning), influence of alcohol, temperaments of interacting parties and the subjects of discussion (Baer et al., 2015; Bassett et al., 2016; Blair, 2001; Hallgren et al., 2015; Kamarajan et al., 2006). Several definitions of executive functioning exist; Lezak (1995) defines it as a collection of interrelated cognitive and behavioural skills and includes the highest level of human functioning such as intellect, thought, self-control, emotional regulation and social interaction.

Mental health studies suggest that social interaction thrives better in people without cognitive impairments, especially ones associated with executive functioning. Thriving social interaction here refers to an interaction where anti-social behaviour is not consistently displayed by the action or inaction of any of the interacting parties. Several studies argue and have attempted to show that inhibition (a key executive function) is crucial in social interaction (Houdé & Borst, 2015). Inhibition during social interaction is often associated with emotional regulation (Sani, Tabibi, Fadardi, & Stavrinos, 2017; Serrano-Ibanez et al., 2018); moreover, some studies have attempted to highlight the interplay between them in the cognitive process (Carlson & Wang, 2007; Gross, 2002). Spinrad and Eisenberg (2014) illustrate the role of inhibition and emotional regulation in interaction by showing how understanding the other person’s emotions during social interaction assists with regulating the flow of interaction and behavioural responses. The other person as defined by Spinrad and Eisenberg (2014) refers to the second party in a conversation. Diamond (2013) links this regulation to executive functioning. Several other studies (Combs, Garcia-Willingham, Berry, van Horne, & Segerstrom, 2018; Garcia-

Willingham, Roach, Kasarskis, & Segerstrom, 2018; Hughes, Power, O'Connor, & Orlet Fisher, 2015; Williams, 2010) argue in line with Diamond (2013), and this further strengthens the link between emotional regulation and inhibition which is a known executive function. One possible deduction from these studies is that anti-social behaviour as a response to stimuli is more likely to be exhibited (disinhibited) by people with deficits of mind associated with executive functioning (Green, Horan, & Lee, 2015).

Disinhibition to stimuli responses appears to be common, albeit at different stages in most known cognitive impairments (Belanger, Belleville, & Gauthier, 2010; Combs, Garcia-Willingham, Berry, van Horne, & Segerstrom, 2018; Oh et al., 2013). Within psychology, paradigms such as Stroop (Stroop, 1935), Simon (Hommel, 1993) and Hayling tasks (Nathaniel-James, Fletcher, & Frith, 1997) have been used to investigate inhibition. Although social interaction deficit has been highlighted in cognitive impairments, care is taken not to assume that the inhibition resulting from these paradigms is the same as inhibition to anti-social response evoked during social interaction. This is particularly difficult to measure because the neural correlates of inhibition are often considered as part of a complex neurocognitive network (Kim, Wittenberg, & Nam, 2017; Ridderinkhof, Van Den Wildenberg, Segalowitz, Carter, & cognition, 2004).

Advances in neuro-imaging have seen the emergence of several non-invasive neuro-imaging tools each with its associated limitations (Anwar et al., 2016; Huettel, Song, & McCarthy, 2004; Lu et al., 2010). Some popular neuro-imaging tools include the functional magnetic resonance imaging (fMRI), the electroencephalogram (EEG), the magnetoencephalography (MEG) and the functional near infra-red spectroscopy (fNIRS) (Papadelis, Grant, Okada, & Preissl, 2015). With these tools, however, the exact relationship between the measured signal from neuro-imaging tool and neural activity is unclear (Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001). The inferences from these tools are mostly drawn from the Blood Oxygen Level Dependent (BOLD) contrast (Ogawa, Lee, Kay, & Tank, 1990; Pfurtscheller et al., 2018) which is suitable for real-time mapping of brain activity under normal physiological condition (Ogawa et al., 1990). Hence blood oxidation maps evoked during an activity can effectively suggest neural correlates emanating from a task. This is however only valid within the limits of the adopted neuro-imaging tool.

Several studies have attempted to study social interaction and interpersonal relations and their neural implications (Goffman, 2017; Hari, Henriksson, Malinen, & Parkkonen, 2015; Sliwa &

Freiwald, 2017). Some of these studies have improved understanding of social cognition and interaction. Hari, Henriksson, Malinen, and Parkkonen (2015) and Schilbach (2006) however suggested that most of what is known in this area are based on the passive spectator perspective rather than the active interactor perspective. Passive spectator here refers to participants playing an observatory role during social interaction, while active interactor refers to participants engaging in social interaction through both verbal and non-verbal cues. To investigate social interaction from the active interactor perspective, it is important to highlight the cruciality of inhibition to social interaction as mentioned earlier.

To investigate inhibition within an active social interaction, factors such as the interpersonal distance of interacting parties (Ashton, Shaw, & Worsham, 1980; Sorokowska et al., 2017) and cultural implications of gestures (Remland, Jones, & Brinkman, 1995) need to be considered. It is also imperative for experimental conditions and platforms to reasonably support naturalistic conversations.

The likelihood of fatigue in human confederates as a result of carrying out the same task multiple times, the cost of recruiting trained confederates and repeatability of experiments suggest a need for virtual human confederates. We know from previous studies that virtual humans are capable of showing verbal and non-verbal cues and gestures (Leavitt, Keegan, & Clark, 2016); we also know from studies on Human-Computer Interaction (HCI) that these attributes are fundamental to social interaction (Edmiston et al, 2013). Virtual humans adopt similar technology as conversational agents which are key elements of HCI. Consequently, we believe that understanding conversational agents will be significant in virtual human communication cues. We argue that the absence or inadequacy of the right verbal and non-verbal cues takes away the possible advantages of using virtual human confederates over other possible alternatives such as audio and video recordings where these cues might not be shown at all or in sync.

Meanwhile, immersive Virtual Reality (VR) presents numerous advantages compared to their non-immersive displays, one of which is the fact that agents and objects can be represented in novel multidimensional formats in shared spaces (Psotka, 1995). We argue that an immersive VR system will potentially present a more viable option to evoke the intended neural responses. VR also brings the advantage of carrying out experiments in controlled environments (Nolin et al., 2016).

The neural basis of inhibition to VR generated stimuli has been previously explored (Landowska, Roberts, Eachus, & Telemedician, 2017). However, VR studies within the social domain have focused mostly on the perception of confederates, social cognition and therapies for public speaking and phobia for crowd (Bera, Kim, & Manocha, 2016; Botella et al., 1999; Nakada, Chen, & Terzopoulos, 2018). None of these VR studies has targeted neural response indicative of inhibition during social interaction with virtual humans. This research, therefore, attempts to fill this gap.

1.2 Aim

To trigger and measure neural response indicative of inhibition during social interaction with virtual human(s).

1.3 Objectives

- Develop a technology platform suited to evoking anti-social behaviour and measuring the associated neural response (indicative of inhibition), by combining immersive/non-immersive VR, virtual humans, neural imaging and video recording.
- Undertake an experiment to measure neural responses indicative of inhibition to anti-social behaviour using the developed system.
- Administer a known test of inhibition and measure performance in the test.
- Administer a questionnaire to measure the perception of virtual humans.
- Compare the outcome of the experiment with the performance during the Hayling sentence completion task to investigate if neural activity during experiment correlates with Hayling task performance which is a known test of inhibition.
- Compare activation of the medial and dorsolateral prefrontal cortex (PFC) in friendly and unfriendly conversation, with virtual humans.

1.4 Research Questions

- Are virtual humans capable of triggering measurable prefrontal cortex (PFC) responses in real humans during social interaction?
- Is this neural response indicative of inhibition?
- What kind of display system is best suited to study this?

Details in Chapter 3, Section 3.6.

1.5 Contribution

This study will potentially contribute to the existing bodies of knowledge in Virtual Reality (VR), Neuro-Imaging and social/cognitive Psychology. It identifies and attempts to fill a gap in the application of VR, virtual humans, neuro-imaging and the intersection of these fields. It targets neural response to anti-social behaviour vis-à-vis inhibition. Anti-social behaviour here refers to any behaviour that is either socially unacceptable or indicative of verbal aggressiveness.

The findings from this study have potential application in behavioural therapies for individuals with a history of anti-social behaviour as well as cognitive impairments associated with lesion within the frontal lobe. The potential application in behavioural therapy stems from the fact that the proposed system is capable of controlled exposure of these individuals to an aggressive and confrontational conversation, which can in turn trigger similar responses from these individuals. These responses can subsequently be evaluated and further provide useful cues to subsequent studies. Moreover, the proposed system is one that can be installed in home owned commercial devices, as such, therapies can be carried out remotely based on the recommendation of therapists.

1.6 Ethical Considerations

Ethical approval was obtained from the Health Science Research ethics panel. A major consideration in obtaining ethical approval was the proposed choice of technology. A plausible concern emanating from the choice of technology was alleviated by the fact that a similar study within the group sought and obtained ethical approval approximately twelve months before this study. Meanwhile, the content of the experimental task was carefully examined not to promote vices such as hate speech and racism. Details of this approval are discussed within the methodology chapter and each of the individual studies. The ethical approval number for these studies is HSR1617-90.

1.7 Meta-Methodology

A review of existing works of literature in the fields of Virtual Reality (VR), Virtual Humans, Neural sciences/Neuroimaging, Social Interaction, Antisocial behaviour, Executive Functioning, Inhibition, cognitive impairments and the associated theoretical frameworks was carried out and gaps identified. Subsequently, research questions were also formulated.

Three experiments, all targeting a healthy population were carried out to answer these questions. Healthy, in this case, shall represent participants with no diagnosis of cognitive impairments or mental deficit.

The first experiment adopts a virtual reality head-mounted display (HMD).

The second experiment was carried out using a large 50-inch display screen. The second experiment sought to overcome the problems encountered in the first experiment and compare the results.

A third experiment took the results and observations of the first two experiments into consideration. It adopted a system of projectors referred to as the immersive suite.

For all three experiments, a VR simulation was built which allowed participants to engage in social interaction with virtual humans. Since display media varied across experiments, the required plugins for each display medium was exported to a memory stick with a compatible executable file. The systems were designed using a software development life cycle (SDLC) method suitable for the design of VR systems and virtual humans (this is discussed subsequently). Prefrontal cortex (PFC) activity was measured using the functional near infrared spectroscopy (fNIRS) during the experiments and the quantitative data analysed. Participants' perception of virtual humans was captured using the Godspeed questionnaire series and analysed for all three experiments.

Meanwhile, a standard test of inhibition was administered and analysed for the first two studies. The results of the test of inhibition in each study were compared to the task-related neural activity in their corresponding studies. The outcome of the comparison suggested no relationships between performance in the test of inhibition and task-related neural activity during the experiments. Consequently, the test of inhibition was not administered in the third experiment. Moreover, we argue that the number of participants in the combined experiments may not have been enough to run a statistical correlation on the resulting data.

1.8 Structure

An outline of the structure of the thesis is provided below.

Chapter 2: Literature Review

Chapter 3: Methodology

Chapter 4: Experiment 1

Chapter 5: Experiment 2

Chapter 6: Experiment 3

Chapter 7: Conclusion and future work

CHAPTER 2

LITERATURE REVIEW

2.0 Chapter Overview

In this chapter, we report our review of works of literature. It is worth noting that most of the review here was done at the start of the PhD and although review continued throughout the PhD, subsequent reviews are contained in the respective chapters of relevance.

2.1 Introduction

The current study focuses on triggering and measuring neural inhibitory responses to stimuli in humans immersed in social interaction. We identify useful cues from existing studies. We consider studies that have:

- focused on triggering responses to stimuli, technologies adopted by these studies and suitability of these technologies to our study.
- attempted to quantify or measure responses to stimuli, the technologies adopted or recommended by these studies and the suitability of these technologies to our study.
- focused on executive functions, with particular interest in inhibitory control and paradigms adopted by these studies.

In line with the considerations listed above, we structure our review as listed below:

- Virtual Reality
- Applications of Virtual Reality (Virtual Humans and Avatars)
- Social Interaction
- Neuroimaging
- Inhibition

We conclude this chapter with justification for the focus of this study and adopted technologies. We also provide relevant information upon which our methods are built.

2.2 Virtual Reality (VR)

The First VR system was built in 1968 by Ivan Sutherland (Pausch, Proffitt, & Williams, 1997). VR has its origin from the ability of modern computers to simulate the interaction of the human senses with the physical world (Deering, 1993). We observe that VR is often linked with 3D graphics display; however, the existence of a first-person viewpoint and a head tracking device differentiates a well-designed VR system from regular 3D graphics display systems (Deering, 1992). Existing VR Technologies include Head-Mounted Displays and CAVE Automatic Virtual Environments (Ip et al., 2018; Pausch et al., 1997). Augmented Reality (AR) is also becoming increasingly popular and is often used interchangeably with VR (Baus & Bouchard, 2014). Baus and Bouchard (2014) also highlighted the potentials of AR in exposure therapy; we, however, will not explore AR within this study.

2.2.1 Head-Mounted Displays (HMD)

The first known VR system was an HMD (Pausch, Proffitt & Williams, 1997). A head-mounted display consists of two LCD screens mounted in a glasses-like device and fixed relative to the wearer's eye position and portrays the virtual world by obtaining the user's head orientation (Santos et al., 2009). Traditional HMDs are fully immersive; however, they are more likely to cause simulator sickness (Koch, Massimini, Boly, & Tononi, 2016).

HMDs appear to be more commercially viable than CAVE systems (de Borst & de Gelder, 2015); therefore, they are more readily available for public use. The commercial viability of HMDs is further shown by Tong and colleagues (2016), who highlighted the affordability of modern-day HMDs.

HMDs are suitable for the current study as they are relatively portable. Moreover, we argue that HMDs have a higher likelihood of being deployed in homes as they are generally affordable. Deploying a system in homes brings the advantage of making it accessible to patients that may have difficulty commuting to see therapists. It also brings the potential of gathering patient data remotely to enhance therapy (Huang et al., 2014). The Oculus Rift and HTC VIVE are two impressive "commodity VR" HMDs (Young, Gaylor, Andrus & Bodenheimer, 2014). Commodity VR here refers to low cost, but functional VR devices. Suznjevic, Mandurov and Matijasevic (2017) attempted to compare the performance of these devices by collecting user ratings of overall quality, perceived ease of use and perceived intuitiveness. The results indicated that the HTC VIVE slightly outperforms the Oculus Rift. This inference was drawn from a VR pick-and-place task. A pick-and-place task is a common activity in VR which involves picking virtual objects and placing them in a specific location in the virtual environment while points are scored based on accuracy. This task may not have been the best task with which to compare these devices; the slight outperformance only suggests a minimal distinction between the two devices. We argue that the difference in performance between the two devices will not be significant enough to alter our results based on an eventual choice of any of the two. The HMD, however, has several disadvantages ranging from the inability of users to view their bodies (Langerak, Prince, Herdman, & Wade, 2016) to inability to have a therapist in the same VR simulation as a participant during an intervention (Ip et al., 2017). Ideal social interaction scenarios may involve more than one person (Lavorgna et al., 2017); moreover having real humans with virtual humans in the same simulation may enhance the quality of the simulation. However, involving real humans defeats the purpose of the current study which is primarily interested in virtual humans and suggests them as viable alternatives to real humans.

2.2.2 The CAVE Automatic Virtual Environment (CAVE)

The CAVE is fully immersive and unlike HMDs, it allows for convenient movement within tracked areas (Cali et al., 2016).

A typical CAVE consists of rear projection screens for walls, a downward projection for the floor, projectors, computer-controlled audio and motion tracking devices (Cruz-Neira, Sandin, & DeFanti, 1993). CAVE systems have been widely explored by several studies (Suznjevi et al. 2017). Interpersonal distance and eye gaze monitoring are also apparently better managed in CAVEs (Iachini et al., 2014). The CAVE is best suited for interventions that require both the therapist and the participants in the same simulation (Ip et al., 2017) as well as cases where participants may be interested in visualising their bodies (Langerak et al., 2016). The CAVE is less likely to cause simulator/motion sickness compared to HMDs (Young et al., 2014); however, the adoption of the CAVE for this study is challenged by such factors as cost and mobility. Traditional challenges with CAVE systems include cost, inability to project on both sides of screens, the fragility of CAVE components (such as screen, tracker and glasses) and absence of advancements in CAVE technologies capable of matching those within other branches of the computing community (Cruz-Neira et al., 1993); these challenges still abound in CAVE systems (Ritz & Buss, 2016).

2.2.3 Augmented Reality

Augmented Reality (AR) enhances the real environment with virtual reality (Liao & Humphreys, 2015). It also allows for interaction between real and virtual objects within the same space (Ducher, 2014).

AR tends to eliminate many of the external cues that differentiate more traditional VR from Physical Reality (Fernandes, Wang, & Simons, 2015); however, it faces numerous challenges (Levin, Magdalon, Michaelsen, & Quevedo, 2015) which ranges from the number of technological devices required to implement them to the difficulty in implementing haptic feedback in AR. Haptic feedback refers to the use of touch to communicate with users. Although AR appears to be promising, only a few research works have focused on it.

2.3 Virtual Reality Applications

The use of Virtual Reality (VR) to produce desired stimuli has become popular especially in studies bordering around phobia and exposure therapy (Hoffman, 2004; Powers & Emmelkamp, 2008). Hoffman (2004) investigated the impact of VR on subjective pain ratings (analgesia) using fMRI. While this study does not exactly relate to our study, the results showed direct modulation of human brain pain responses by VR distraction, which suggests that neural correlates to VR stimuli indeed exists. Studies of higher relevance would be those where neural correlates in real-world activities are measured against neural correlates in similar VR simulated activities. VR studies are being increasingly applied to health, psychology and training (Koch et al., 2016). VR is also increasingly being used in the assessment of cognition, emotions and behaviour in an ecologically valid and controlled environment (Sakaguchi, 2005). However, psychometric tests exist that target cognition and can be argued to sufficiently provide empirical evidence to cognitive functions after VR interventions. This is also a common pattern with VR exposure therapy where psychometric tests for evaluating cognitive functioning are administered after VR therapy just the same way they were done traditionally (Gerardi et al., 2008). Gerardi and colleagues (2008) presented a case report of using VR exposure therapy (virtual Iraq) to treat returning veterans of Operation Iraqi Freedom (OIF). Following the VR exposure therapy treatment, the veterans demonstrated improvement in PTSD symptoms as indicated by clinically and statistically significant changes in scores on the Clinician Administered PTSD Scale (CAPS; Blake et al., 1990) and the PTSD Symptom Scale Self-Report (PSS-SR; Foa, Riggs, Dancu, & Rothboam, 1993). Gerardi and colleague (2008) is a highly significant study because its results were based on clinical and statistical evidence.

Although this study also fails to provide neural correlates to back up its evidence, its significant findings and subsequent wide adoption of virtual Iraq suggests that these psychometric tests and scales are indeed sufficiently presentable as empirical evidences.

VR offers an option to produce and distribute standard reusable simulation environments which are similar to real-world functional environments (Rizzo et al, 2009). Rizzo and colleagues (2009) provided a review for a VR simulation of a classroom which was initially developed as a controlled stimulus environment in which attention process could be systematically assessed in children with attention-deficit/hyperactivity disorder but was later applied to other clinical targets including tests that addressed other cognitive functions. Whilst Rizzo and colleague (2009) strongly suggests that VR presents a means through which cognition can be assessed, the study fails to highlight any neurological component to strengthen its argument.

Meanwhile, a few studies have compared VR generated stimuli with real-life stimuli, but these studies often lack rigour (Rose, Attree, Brooks, Parslow, & Penn, 2000). Rose and colleagues (2000) focused on training in virtual environments and attempted to investigate if skills gained in virtual environments can be compared to the real world. In this study, real-world performances after were compared after virtual training, real-world training and no training. Performance after virtual and real training was equivalent, both of which significantly exceeded performance after no training. Interestingly, this study further suggests that real-life performance after training in virtual environments is less likely to be affected by concurrently performed interference task than real-life performance after real-life training. This finding is attributed to the capability of VR to enable experiments in a controlled environment where concurrent interference tasks can be introduced as controlled variables. This is not easily achievable with real-life applications. Kozak and colleague (1993) investigated the transferability of skills learned in VR to real life. Like Rose and colleagues (2000) (a later study), Kozak and colleagues (1993) investigated participants' performance in a real-world task after undergoing virtual, real-world and no training. Their findings suggested that the skills gathered in virtual training environments are not transferrable. There was no significant difference between the virtual reality training group and the group that received no training; however, the group that received real-world training performed significantly better. Although Rose and colleague (2000) adopt a similar methodology to Kozak and colleague (1993), the findings are in sharp contrast to each other. Considering the growing sophistication and improvement in the design VR and VR related technology over the years, we agree more with Rose and colleagues (2000) which adopts an improved immersive virtual environment (IVE) set-up with improved tracking and spatial resolution. Meanwhile, the ease with which real-life scenarios can be recreated in VR appears to have increased with time; the contrast in the findings can also be attributed to an assumption of an improved VR simulation by Rose and colleagues (2000) compared to Kozak and colleagues (1993). Meanwhile, VR has also found useful application in behavioural therapy, especially where the subjects have shown difficulty with generating the desired stimuli from their imagination or static images. VR has been useful in generating the desired and more realistic stimuli. The increase in the adoption of VR for this purpose also further suggests the suitability of VR for generating stimuli similar to real-life stimuli.

The use of VR to combat psychological disorders was first conceived within Human-Computer Interaction (HCI) Group at Clark Atlanta University in November 1992 (Ritaetal, 1998), this explains the relationship between VR and HCI. Findings around VR exposure therapy (VRET) further suggests the similarity between VR generated stimuli and real-life stimuli. Morina, Ijntema, Meyerbröker, and Emmelkamp (2015) conducted a meta-analysis of clinical trials applying VRET to specific phobias and measuring treatment outcomes. Fourteen clinical trials were included in this study and results revealed that patients undergoing VRET performed significantly better on behavioural assessment after treatment than before treatment. The study further argued that the results of behavioural assessment post-treatment and follow-up did not reveal any significant differences between VRET and exposure in vivo (carried out in real-life situations). This study strongly supports the viability of VR in treating phobia; however, it fails to suggest the applicability of VR to areas outside the phobia and disorders specified by the study which includes social phobia, agoraphobia and post-traumatic stress disorder and anxiety disorders.

Although VR is increasingly being adopted in psychology, not many studies have combined VR and neuroimaging to measure neural correlates of VR stimuli (Schilbach, 2006). Most indicators to VR perception within psychology are often based on standardized questionnaires. Functional neuroimaging tools such as the fMRI and PET have also been employed especially in studies cutting across the fields of psychology and neuro-imaging, however, these tools have methodological constraints to measure neural responses to stimuli when natural movement is required (Suda et al., 2010). This is a result of tools like FMRI and PET requiring subjects to lie down on a bed in a small noisy gantry during examination (Singer et al., 2006); it makes these tools unsuitable for measuring neural responses within our domain of interest where natural movement and gestures are inevitable. Subsequently, the functional near infrared spectroscopy (fNIRS) was introduced; it showed a huge promise, especially with allowing for naturalistic movement (Dai et al., 2018). This has rekindled a new interest in investigating the neural correlates of day to day activities (Suda et al., 2010). Suda and colleagues (2010) carried out a neuro-imaging experiment during face to face conversation. The conversation involved an interviewer, which was selected from three male psychiatrists and an experimental subject. They engaged in a timed conversation which consisted of six cycles of 30 seconds talk (adding up to 180 seconds). The conversation was limited to anything food and task performance was measured by the number of words within the specified time, and then the content of the talk. The scoring was done by psychiatrists with a minimum of eight years of clinical experience and correlated with the neuro-imaging result. The results of this study showed activity in the frontal lobe and interior gyrus, which is in line with previous studies that have highlighted the concept of the social brain (Frith & Frith 2007). Frith and Frith (2007) highlighted the medial prefrontal cortex, the inferior frontal gyrus and the amygdala as parts of the social brain. As a result of the limitations of the NIRS, results could only be investigated in terms of the medial prefrontal cortex (MPFC). This study highlights the resources needed to complete experiments of this kind. However, funds for trained psychiatrists and therapists may not be readily available; this makes a case for VR alternatives in similar studies.

The cognitive theory of multimedia learning states that people learn deeper and better from words and pictures together (Mayer, 2002); this suggests that VR is a promising medium for intervention delivery as it easily incorporates both as well as evidence-based learning which is effective for exposure therapy (Freeman et al., 2017). Evidence-based learning refers to a collection of processes, approaches and methods that have been empirically demonstrated to produce learning outcomes; VR presents a possibility of recreating these strategies. VR has also featured in studies on social interaction and interpersonal space (Bailenson, Blascovich, Beall, Loomis, & Bulletin 2003; Raij et al., 2007; Robitaille et al., 2016); the outcomes from such studies appear to have significantly impacted design of VR systems focusing on the social domain.

2.3.1 Virtual Humans (VH)

Albright and colleagues (2016) defined virtual humans as automated, three-dimensional agents that converse, understand, reason and exhibit emotions. Swartout and colleagues (2006) also defined virtual humans as autonomous agents that support face-to-face interaction with people in virtual environments. Blascovich and colleagues (2002) however suggest that virtual humans can either be completely autonomous, fully controlled or semi-autonomous; in line with this, we argue that semi-autonomous and non-autonomous virtual humans exist. An autonomous character is one whose decision making comes only from a set of computer programmed algorithms/logic; a semi-autonomous character has only part of its decision making coming from computer programmed logic and other parts of it coming from humans through button presses or motion capture; while a fully controlled character is one whose decision making comes from human activity such as button presses or motion capture. Allport (1985) social psychology study contributes significantly to our knowledge of virtual humans. This study highlights social influence as the primary subject matter of social psychology and further suggested three distinctions for social influence, which include actual, implied and imagined presence of others. The actual presence of others in this study represents scenarios where an actual representation or symbol of others is present within a scene and responds to social stimuli in real-time. An example of the implied presence of others in this study is a scenario where one thinks about how members of an intended audience will receive what will be conveyed. Finally, an example of the imagined presence of others is a scenario where children often play with imaginary playmates and are frightened by the imaginary presence of scary characters. Although Allport (1985) suggested that the effect from either of these distinctions is equivalent, we agree with Blascovich and colleagues (2002) and Dufner and colleagues (2013) which argued that actual presence conveys gestures and movements that make interaction more believable. This argument is also consistent with Jones and colleagues (1998), however, Jones and colleagues suggested the possibility of distinct findings when social psychology is considered across cultures. Meanwhile, Hill (2006) in his survey of texts on social psychology argued that much of applied social psychology lack theoretical analysis and is yet to use the kind of theory needed to understand social problems. Hill (2006) further argued that most mainstream texts on this subject seemed highly individualistic, rarely focused on important issues and were increasingly difficult to replicate. As a potential solution, Hill (2006) highlighted the emergence of critical psychology which entails renewed attention to the limits of generalizability and the importance of knowing and understanding contexts. The issues highlighted by Hill (2006) links back to the problems of social psychology listed by Allport (1985), especially, “experimental control – mundane realism trade-off”. The other problems highlighted by Allport (1985) are “lack of replication” and “nonrepresentative sampling”. Experimental control – mundane reality trade-off here refers to the balance between precise manipulation of independent variables (experimental control) and the extent to which an experiment is similar to what is encountered in everyday life (mundane reality). Restricting social psychology experiments to well-defined domains and contexts as highlighted by critical psychology (Hill, 2006) enhances the balance between experimental control and mundane reality (Allport, 1985). Meanwhile, lack of replication refers to the difficulty (impossibility) associated with recreating experiments in social psychology, especially because of the problem of replicating emotions even when trained actors are used. Finally, nonrepresentative sampling refers to the problem of randomly assigning participants to conditions and the difficulty with replicating the sampling of participants in other experiments to accurately compare results. We agree with this study that immersive virtual environments (IVE) offer a promising approach to minimise or even alleviate this problem. Although IVEs present a means to account for the actual, implied and imagined presence of others (Allport, 1985), the focus of this study is on actual presence, which has had its scope redefined in recent times by technology such as telecommunications, telepresence, motion tracking devices and indeed IVEs. Virtual humans also fall into this category (Blascovich et al., 2002); they also bring the advantage of repeatability which is a problem highlighted by social psychology as highlighted by Allport (1985) and subsequently Blascovich and colleagues (2002).

Virtual humans apply to a wide range of activities, especially ones that require live exercises, role-playing, conversations aimed at driving meaningful change in behaviours and attitudes (Albright et al., 2016; Swartout et al., 2006). VR presents the option of carrying out experiments in a controlled environment (Albright et al., 2016). This is also true for VR applications in the social domain, especially virtual humans as it applies to this study. Albright and colleagues (2016) suggest the ability of virtual humans to improve physical and mental health. Their usage in role-play as alternatives to real human trainers has significantly increased their usage in the mental health domain. Albright and colleagues (2016) also argued that virtual humans present a less costly alternative to trained actors, they are also capable of conveying the same mannerisms across users during conversational tasks, which makes them suitable for conversational experiments and trials. Although Albright and colleagues (2016) captured the usefulness of virtual humans and its potential application especially within the mental health domain, its focus was on learning theories and role play; therefore, it does not strongly justify the use of virtual humans as intended in this research. Meanwhile, Robitaille and colleagues (2016) argued that adding human interaction through avatars increases the ecological nature of social environments. This suggests that virtual humans/avatars are capable of conveying human-like interaction; this argument is further strengthened by Raij and colleagues (2007), which compared interpersonal interactions with a virtual human to that with a real human and suggested that socially relevant human gestures can be conveyed by a virtual human.

Blascovich and colleagues (2002) developed a threshold model for social influence. They hypothesized that social influence will occur in IVEs as a function of two additive factors: behavioural realism and social presence. Behavioural realism refers to the degree to which virtual humans or objects within IVEs behave as they would in the physical world, while social presence refers to the degree to which users (e.g. participant) in an IVE believe they are in the presence of and interacting with another veritable human being which displays actions that represent those of actual humans in the real world. This model suggests a key consideration in the design of virtual humans. The study, however, noted that behavioural realism differs from photographic realism. Photographic realism is only an aspect of behavioural realism and Blascovich and colleagues (2002) argued that it is only minimally relevant. This is also a well-accepted belief amongst cartoonists (Ng et al., 2007).

Virtual Humans and Avatars have been major topics in Human-Computer Interaction (HCI) within the past decade. Whilst some studies have attempted to show that VHs are perceived the same way as real humans, the empirical evidence provided by these studies are often inconsistent (de Borst & de Gelder, 2015); hence the conflict in opinions around the perception of VHs. de Borst and de Gelder (2015) linked perception with emotions in humans. The study argued that facial expressions alone do not sufficiently account for emotion, thus the perception of emotions in their study was considered in line with neural levels and emotional body languages. Unlike classic VH studies that focus majorly on facial expressions as a tool to convey emotions, de Borst and de Gelder (2015) investigated whole-body signals and reported that emotional information from the face, voice, body motion and posture often highlight and intensify the emotion expressed in the face and the voice. The implementation of these features in VH is however not trivial and the lack of them in VH studies may be responsible for the conflict in opinion on perception of virtual humans.

The current study targets perception of VHs on one hand and the neural responses evoked by them on the other hand. We attempt to provide empirical evidence to neural responses evoked by VHs. Studies on neural sciences and neuroimaging suggest that different parts of the brain are responsible for different stimuli responses. It is therefore important to ascertain the parts of the brain implicated during social interaction and possibly measure the neural correlates. Studies also suggest that neural correlates exist for all cognitive activities (de Borst & de Gelder, 2015; Koch et al., 2016; Yang et al., 2016). Schilbach and colleagues (2006) observed interaction with virtual humans from a participatory point of view on one hand and an observatory point of view on the other hand. In this fMRI study “being with virtual others”, neural correlates of interaction with a VH when a participant is personally involved in social interaction on one hand (ME) and a passive observer on the other hand (OTHER) were investigated. Social interaction in the context of this study was considered in terms of facial expressions. In the OTHER condition, virtual characters dynamically showed socially relevant (SOC) and arbitrary facial expressions (ARB). Increased neural activity associated with (ME > OTHER) was shown in the anterior medial prefrontal cortex, while the perception of socially relevant facial expression (SOC > ARB) was associated with the ventral medial prefrontal cortex. This study showed the involvement of the prefrontal cortex (PFC) areas in social interaction with corresponding increased activity in comparison to baseline in these regions. We, however, argue that increase in activation compared to baseline alone may not be strong enough evidence to conclude as the study does not clearly show that the neural correlates are triggered by social interaction with the virtual humans alone. Our argument is based on the observation that no prior procedure was put in place in this study to ensure that neural activity may not have been influenced by participants excitement with the virtual environment. We believe that a procedure aimed at eliminating this effect is essential for a study like this, especially for an fMRI study where neural correlates are only measured at the end of the procedure.

The combination of virtual humans and neural imaging in as utilised by Schilbach's study was of significant interest to this PhD. The PhD builds on some of the shortcomings of Schilbach's study which are the unsuitability of the fMRI for conversational tasks, the non-depiction of mundane realism in representing a conversation with only non-verbal cues as well as the earlier mentioned attempt at eliminating the effects emanating from participants' excitement within the virtual environment.

2.4 Social Interaction

As a crucial part of our daily activity, we engage in interaction with people for different purposes (So et al., 2016). The brain is heavily involved in person to person interaction and these interactions appear to thrive when interacting parties are mentally stable. Stability of the mind, however, is subject to factors that vary from person to person. Social interaction brings together different parts of cognition and emotions and has been a focus of studies that have focused on social disorders such as Autism Spectrum Disorder (ASD) and Tourette's syndrome amongst others.

During social interaction, understanding the emotional state of the other party is important and could be useful in communication and reciprocal interaction (Keltner & Cordaro, 2017). However, verbal and non-verbal cues are perhaps more important, especially when both parties are involved in face to face conversations. Studies across disciplines such as neuroimaging, human-computer interaction, virtual humans and social cognition are becoming increasingly interested in exploring verbal and non-verbal communication, therefore we attempt to elaborate on them below.

2.4.1 Verbal Communication

In verbal communication, words and sounds are used in self-expression. Verbal Communication is fundamental to social interaction, especially in cases where linguistic structures are applicable (Keltner & Cordaro, 2017). Verbal cues exaggerate words and sounds (Burgoon, Guerrero, & Floyd, 2016); however, the extent to which they can exist without non-verbal components is unknown.

The way people engage in verbal interaction varies from person to person. While there may be other factors responsible for this variation, it is mostly accounted for by non-verbal cues such as tone, pitch and volume (Clark, 2016). Several studies have argued that verbal cues account for less during social interaction when compared to non-verbal cues (Argyle, 1972; Riggio, 1992; Kacperck, 1997). However, we do not have enough basis to draw this conclusion. This is because we did not find any study that compares these cues distinctly.

2.4.2 Non-Verbal cues

Central to social interaction and information processing is body states such as postures, arm movement and facial expression (Lindblom, 2015). These body states, also referred to as non-verbal cues have become key factors in communication studies and Human-Robot interaction (Han, Campbell, Jokinen, & Wilcock, 2012). Tone, rate, volume, pitch and pauses are also key elements of non-verbal communication (Kiani, Balouchi, & Shahsavani, 2016; Spieler & Miltenberger, 2017). The tone of a speech affects a listener’s perception of aggressiveness or calmness of the speaker (Spieler & Miltenberger, 2017). A sentence may represent two different meanings depending on the tone of the speaker. Rate refers to the speed with which words follow each other during a speech (Nikolaidis, Kwon, Forlizzi, & Srinivasa, 2017). Clark (2016) suggests that rates convey different thoughts and feelings for different individuals. People tend to speak at faster rates when they are either tense or angry; this may vary slightly with naturally fast speakers, however (Clark, 2016). Volume refers to the loudness of a speaker’s voice. Loud speakers often come across as aggressive and authoritative; findings around anger management show that speech volume tends to increase as aggression or anger increases (Hussain et al., 2017). Similar to volume is pitch which refers to the highness or lowness of a speaker’s voice (Hussain et al., 2017). This is often obvious when a speaker attempts to emphasize on an issue. Pitch appears to be more obvious in female speakers than it is with their male counterparts. Pauses are also useful elements in verbal interaction. Pauses tend to add expression and feelings to a speech. They appear to be mostly used at the start of expressions, or between expressions to emphasize a distinction between them (Kiani et al., 2016; Spieler & Miltenberger, 2017).

Non-verbal communication exaggerates gestures and mannerisms as opposed to words and sounds in verbal communication (Burgoon, Guerrero, & Floyd, 2016). The gestures and mannerisms displayed in non-verbal communication are believed to convey deeper emotions than verbal cues (Remland, 2016). However, we were unable to find any study that has attempted to quantify the cues to compare them.

Han and colleagues (2012) report that a substantial part of the interaction is carried out through non-verbal channels. While we are careful not to pitch the importance of non-verbal cues above the verbal ones, we believe that verbal communication cannot exist without non-verbal cues (Haynes, 2017). For instance, a conversation between individuals with speech or hearing impairments may not thrive without non-verbal cues because cues such as tone and volume are classified as non-verbal (Hussain et al., 2017). These cues convey the state of emotions of verbal communication. We note however that the same can be said of verbal communication; an example is a conversation between blind people.

Different gestures pass different messages during interaction (Pease & Pease, 2016). For instance, punching the air with a strong fist reflect intensity, while two hands wide open with a shoulder shrug shows uncertainty (Cracco, Genschow, Radkova, & Brass, 2017). Gestures complement verbal communications, but can also stand on their own (Haynes, 2017). Individual mannerisms and mental deficits can also affect the presentation of gestures (Georgescu, Kuzmanovic, Roth, Bente, & Vogeley, 2014).

Eye gazes (including avoidance of gaze) and interpersonal distance appear to be an interesting non-verbal cue as suggested by studies around social anxiety (Howell, Zibulsky, Srivastav, & Weeks, 2016; Walther, Van Der Heide, Ramirez, Burgoon, & Peña, 2015). Howell and colleagues (2016) investigated the relationship between trait social anxiety, eye contact avoidance, state anxiety and participants’ self-perceptions of interaction performance during a live conversation via webcam while being eye-tracked. The results from this study indicated that trait social anxiety was inversely related to eye contact duration and frequency averaged across the length of the conversation. Trait social anxiety refers to the stable tendency to experience nervousness in social situations (Howell, Zibulsky, Srivastav, & Weeks, 2016; Karasewich & Kuhlmeier, 2019). Howell and colleagues (2016) further found that trait social anxiety was positively related to state social anxiety and negative ratings. This suggests an inverse relationship between eye contact duration and state social anxiety as well as negative ratings. State social anxiety refers to the momentary response given to a particular social situation. Understanding these interesting relationships is key to creating virtual human confederates that convey the desired appearances and social anxiety state.

We expect increased neural activation relative to baseline measures within the regions of interest (ROI) in our participants with decent implementation of the highlighted verbal and non-verbal cues on virtual characters.

2.5 Neuroimaging

One of the interests of this study is to evaluate the neural response to VR/VH generated stimuli. Some technologies that have been effective in achieving this include Positron Emission Tomography (PET), Electroencephalography (EEG), Functional Magnetic Resonance Imaging (fMRI), Functional near Infrared Spectroscopy (fNIRS) (Klein, 2010; Strait & Scheutz, 2014). This is not primarily a neuro-imaging study; consequently, this review only seeks to justify the chosen technology.

Neuroimaging technologies have their strengths and weaknesses as expected (Cui, Bray, Bryant, Glover, & Reiss, 2011). Klein (2010) argues that neuroimaging (fMRI in particular) is exploratory rather than confirmatory; this suggests that results from fMRI studies should be subject to further investigation. Exploratory in this context refers to a proof of concept, while confirmatory refers to proof backing existing pieces of evidence. Klein (2010) in his review of the debates over the evidential status of fMRI, however, failed to disprove the results from any neuroimaging study that have adopted the fMRI.

The choice of neuro-imaging tools has often been guided by research interest and availability of technology and funds. The current research is concerned with inhibition during social interaction and we expect the medial prefrontal cortex (MPFC) and dorsolateral prefrontal cortex (DLPFC) to be implicated during interaction and their associated inhibition (Frith, 2007). Evidence from literature suggests that the DLPFC is involved in cognitive control (Riling et al, 2009), while the MPFC is part of the social brain and is implicated during social activity (Frith, 2007). Further details as regards our interest in these regions is provided in subsequent sections. Therefore, we adopt a neuro-imaging tool that is effective in measuring PFC activity. We acknowledge that measuring beyond the PFC may provide better results; however, we restrict our choice to availability of tools. We further justify our choice with the promising result shown by similar research within the group.

2.6 The Prefrontal Cortex

The prefrontal cortex has been long believed to be associated with behavioural activity and its deficit. This belief is largely linked with Jacobsen (1935), which demonstrated for the first time experimentally that extensive bilateral lesions in the frontal cortex induce a permanent behavioural deficit. In this study, the frontal area, the prefrontal area and frontal association area were used interchangeably and as such refer to the same brain region. The study was carried out at a time when little was known about the PFC and it set the tone for subsequent studies seeking to understand this brain region, hence its significance to this review.

Early studies associate the PFC with short term memory (Fuster, 1973; Kubota & Niki, 1971). This opinion was drawn from an understanding that lesions in the PFC cause in delayed response tests. Fuster (1973) described delayed response trials as consisting of the presentation of one or two visual cues, an ensuing period of enforced delay and a choice of motor response in accord with the cue at the end of it. In addition to delay response performance, Kubota & Niki (1971) suggested that lesions in the dorsolateral PFC especially was also believed to induce permanent deficits. They interpreted these deficits as the loss of immediate or recent memory initially but associated it with behavioural impairments subsequently in line with Jacobsen (1935). Delay response performance appeared to be a common target with these studies which established the link between the PFC and working memory at this time. We note that these studies were mostly influenced by Jacobsen (1935).

Whilst these studies are important in understanding the perception of the PFC in that era, we observed that the studies mostly targeted non-human primates. Markowitsch and Pitzel (1978) while observing the Brodmann areas in primates argued that the number of fields that make up the prefrontal regions in human primates is higher than what is obtainable in non-human primates. These slight discrepancies in the prefrontal region raise concerns as to the viability of their findings; following this, we argue that these studies would have presented a much stronger argument if they had targeted human primates.

A highly significant story that associates lesion in the prefrontal cortex to behavioural deficits is the story of Phineas Gage (Jacobsen, 1935; Steegman, 1962). Initially reported by Harlow (1848), this story has been referenced severally. According to Steegman (1962), Phineas Gage was a railroad foreman who survived to have a metal rod shot through his skull and brain during a work-related accident. As a result of Gage's accident, much of his frontal lobe and prefrontal cortex was destroyed. Gage who was suggested to be a responsible, temperate, hardworking man before his accident; afterwards became capricious, irrelevant and troublemaking and seemed to have lost his ability to inhibit base impulses. This suggests a strong association between the prefrontal cortex and human behaviour, especially inhibition. However, much of the frontal lobe was reported damaged in this accident, one may argue that the behavioural deficits can equally be as a result of the lesion in some other parts of the larger frontal lobe.

The era between 1980 and 1989 was characterised with studies investigating lesions in the PFC (Kesner, Farnsworth, & DiMattia, 1989; Vargo, Richard-Smith, & Corwin, 1989; Isaac, Nonneman, Neisewander, Landers, & Bardo, 1989). Like the previous era, the majority of these studies targeted non-human primates, which questions the validity of the findings, especially concerning this research.

Subsequently, the prefrontal cortex has featured mostly in association with executive functioning. The PFC is believed to account for over ten per cent of the entire brain (McBridge, Arnold & Gur, 1999) and consequently may be involved in more activities than is being reported in previous works of literature.

Brodmann defined a numbering system for brain regions based on the cytoarchitectural organization of neurons in the cerebral cortex (Brodmann, 1909). Although Brodmann areas have been subject to debates and refinement, it remains the most widely known cytoarchitectural organization of the human cortex (Murray et al 2017). Murray and colleagues (2017) posit that in terms of Brodmann areas, the prefrontal cortex traditionally includes the areas 8, 9, 10, 11, 12, 13, 14, 24, 25, 32, 44, 45, 46, 47. Although this study refers to the cytoarchitectural organization of the mammalian brain in general (which we argue defers in complexity to the human brain), it is significant to this research as it creates a reference point for investigating neuro-images.

As mentioned previously, the PFC has been widely linked to executive functioning. Koechlin & Summerfield (2007) suggested a model which proposes that executive functioning is guided by a hierarchically ordered control signal, processed by a network of brain regions, organised along the anterior-posterior axis of the lateral prefrontal cortex. Executive functioning/control in this study is described as an ability to select actions or thoughts in relation to internal goals. This study is supported by evidence from brain imaging and neuropsychological studies in human subjects, and it highlights the involvement of the lateral parts of the PFC (in particular) in executive functioning/control. Roth and colleagues (2006) in their PET study defined executive functions as a set of related cognitive processes that are essential in regulating cognition, emotion and behaviour. Roth and colleagues (2006) also faulted the methodological approach to what had been accepted historically as the neurobiological basis of executive functions. They argued that the approach was largely dependent on lesion studies and led to the widely held belief that the integrity of the frontal lobe is central to executive functions. They argued that lesion studies were unable to investigate the broader neural circuitry. Collette and colleagues (2006) also reviewed studies that have explored the cerebral substrates of executive functions. Although Collette and colleagues (2006) suggests that executive functioning relies on a distributed cerebral network, it acknowledges a pattern in the cerebral areas involved in the different executive functions. Like Roth and colleagues (2006), Collette and colleagues (2006) also highlight the ability of neuroimaging approach as opposed to studies targeting frontal lobe lesions. Meanwhile, Owen (2000) investigated the significance of the lateral regions of the PFC in executive functioning. Unlike the widely accepted assumption that working memory processes within the lateral cortices are arranged according to the nature or domain of the information being processed, Owen (2000) argued that these cortices are arranged according to the type of processing required. This argument is significant to our research since our focus is on neural processing indicative of inhibition and not on strength of participants within the chosen domain. Owen (2000) taking a cue from Stern and colleagues (2000) argued that there is an overlap between the lateral frontal regions implicated in spatial, visuospatial and verbal working memory tasks, which are executive functions. Løvstad and colleagues (2012) further demonstrate that damage in the lateral PFC is prone to cause cognitive executive deficit. In their neuropsychological study, 10 adult patients with lateral prefrontal cortex lesions were compared with 14 adult patients with orbitofrontal cortex lesions and 21 healthy controls. Neurological tests aimed at investigating executive functions were administered. The administered tests include tests of sustained mental effort, response inhibition, working memory and mental switching. The Behaviour Rating Inventory of

Executive Functions (BRIEF-A) was also adopted. The result showed that while the lesion in the lateral PFC is associated with cognitive executive deficit, the orbitofrontal cortex injury was more strongly associated with self-reported dysexecutive symptoms in everyday living. Minzenberg et al. (2009) show a meta-analysis of 41 functional neuroimaging studies of executive function in schizophrenia also showed the involvement of the PFC in executive functioning. However, different aspects of executive dysfunction were examined in this study, including multiple facets of working memory, response inhibition, conflict processing, and problem-solving. These dysfunctions demonstrated deficits across a range of circumscribed PFC regions such as ventrolateral PFC (VLPFC), dorsolateral PFC (DLPFC), ventromedial PFC (VMPFC) and anterior cingulate cortex (ACC). While the PFC is implicated in both studies, the VMPFC and ACC are further highlighted in Minzenberg et al (2009).

Miller et al. (2009) argued that patients with deficits in the PFC exhibit a superficial appearance of normality, however, PFC damage devastates a person’s life. Moreover, this study also suggests that depending on the damaged area of the PFC, cognitive deficits manifest in deficits in inhibition: in which case patients are triggered by cues in their immediate environment; planning: in which case the ability to organize ones basic units of behaviour towards a goal is lacking; evaluation of consequences: in which case patients cannot evaluate the consequences of a given action to adopt what works best; working memory: in which case a short term memory buffer which is key for cognitive activities is not sustained; and learning and using rules: in which case the capacity to learn from experiences is highly impacted. This study is significant in that it shows how executive functioning is affected by lesions in the PFC, but it fails to show which part of the PFC is responsible for the distinct executive functions it highlights. This trend is common and can be attributed to the argument that every cognitive process is accounted for by more than one brain region (Kanwisher, 2010). However, Kanwisher (2010) attempted to highlight the existence of some specialized cortical regions which are central to certain cognitive processes. Unlike most other cortical regions, lesion to these specialised cortical regions are likely to significantly affect those cognitive functions. Kanwisher (2010) in her review identified these regions as the fusiform face area (FFA), parahippocampal place area (PPA) and extrastriate body area (EBA). This review focused on visually presented objects and suggests that each of the identified cortical regions responded selectively to single categories of visually presented objects which include faces, locations/scenes and body parts. Kanwisher defined the FFA as the region found in the mid fusiform gyrus, which is the area on the bottom surface of the cerebral cortex. Kanwisher

(2010) argued that this area responds significantly subjects view faces. The PPA is defined functionally as the region adjacent to the collateral sulcus in parahippocampal cortex. This region responds significantly to images of scenes and locations. Finally, the EBA was identified as a region on the lateral surface of the brain, adjacent to the motor area; this region responds significantly to images of bodies and body parts. Kanwisher (2010) also upholds the authenticity of neuroimaging (fMRI in this case) over lesion studies. Meanwhile, structural and functional deficits in the PFC have been attributed to antisocial and violent behaviour (Striedter, 2005; Yang et al., 2009). Yang et al. carried out a meta-analysis on 43 structural and functional imaging studies. The result from these studies showed significantly reduced prefrontal structure and function in antisocial individuals. This suggests that the PFC is significantly involved in the social domain. This meta-analysis was conducted using 35 keywords relevant to anti-social behaviour and brain imaging. Yang and colleagues (2009) suggested that there is heterogeneity in findings within this domain and it was unclear whether findings applied to psychopaths, non-violent offenders, community-based samples or studies employing psychiatric controls. Thus, one of the inclusion criteria for their meta-analysis was: if a group comparison was used, then the study had to include at least one antisocial group and one control group of either appropriate psychiatric controls or healthy normal subjects. If correlation analysis was used, the study must have had at least one assessment of antisocial behaviour. Antisocial group here is defined as a group that contains individuals with antisocial personality disorder, antisocial behaviour, conduct disorder, opposition defiant disorder, psychopaths, criminals, violent offenders, or aggressive individuals). Meta-analyses were performed using comprehensive meta-analysis, version 2, Biostat. For each study included in the meta-analyses, the effect size was calculated using Cohen's method. As mentioned earlier, findings showed significantly reduced prefrontal structure and function in antisocial individuals regardless of the group they fall into. Effect sizes were significant in both structural and functional studies. Findings highlight the involvement of orbitofrontal, dorsolateral frontal and anterior cingulate cortex in antisocial behaviour and colleagues (2009) underscores the need for longitudinal imaging studies and studies that include female antisocial individuals. Finally, they emphasised the likelihood of multiple regions other than the PFC to be implicated during antisocial and violent behaviour. Consequently, they suggested that future brain imaging studies could usefully focus on regions such as the amygdala, hippocampus, insula and angular gyrus which have been much less studied to date.

In terms of Brodmann area, the human PFC is divided into four regions, the dorsolateral (DLPFC), the ventrolateral (VLPFC), the medial (MPFC) and the ventromedial (VMPFC) PFC (Brodmann, 1909). Brodmann (1909) also defined the caudal prefrontal cortex as part of the PFC divisions. As previously mentioned, the PFC is implicated during executive functioning. Of the PFC regions, the DLPFC is mostly recognised as being responsible for cognitive control and control of emotions (Rilling & Sanfey, 2009). deBeus and Kaiser (2011) also argued that there is a link between deficits in the DLPFC and depression. This study, like several others, also suggested that other frontal regions are implicated during depression. However, the DLPFC is more accessible for treatment. The DLPFC is also significantly involved in decision making in social interactions (Rilling & Sanfey, 2009); this argument is highly relevant to this study as it suggests a neural basis for social interaction. Rilling and Sanfey (2009) carried out a review which was focused on the neuroscience of decision making within social interaction. A limitation of Rilling and Sanfey (2009) is that the study did not review a large body of important work within the broader domain of social neuroscience; perhaps this could have presented a stronger argument. The review highlighted the importance of a network of brain regions in decisions that promote prosocial behaviour. Whilst the likelihood of significant involvement of interior brain regions such as the amygdala and insula cannot be overlooked, this study suggests that the PFC appears to be involved in overriding selfish impulses, valuing abstract and distant rewards and in generating certain prosocial emotions. Amongst other findings, Riling and Sanfey (2009) suggests that the DLPFC is involved in emotional regulation which is fundamental to decision making during social interaction. They also suggest that the DLPFC is involved in exerting cognitive effort to override selfish impulses, as when abiding by fairness norms. Meanwhile, the MPFC is also associated with decision making (Euston, 2012). This suggests an intersection in the activities of the DLPFC and the MPFC. Euston (2012) further argued that the MPFC is associated with memory and consolidation on timescales ranging from seconds to days. The MPFC is also thought to be part of the adult social brain (Grossmann, 2013). Although it has long been thought that the PFC is functionally silent during infancy, Grossmann (2013) attempted to show that the MPFC is involved in the development of social cognitive skills at much earlier stages. Grossmann (2013) reviewed studies that have investigated the MPFC in early social cognition in children. Whilst most of these studies tend to agree that the MPFC is functionally silent during infancy, Grossman (2013) argued that infants tend to possess skills with which to interact with their environment and people. Grossman (2013) gave an illustration as to how infants can identify faces and voices at this stage. The review was able to show evidence of infants' MPFC involvement at the early stages. Following these arguments, one can even argue that the MPFC is more important earlier in development. However, this study alone does not stand as strong enough evidence to conclude this argument. Investigating the feasibility of the existing neuro-imaging tools with infants may also be a step towards providing a more concrete argument. This study highlights the importance of the MPFC within the social domain and thus its significance to our research.

2.7 Executive Functions

The executive functions (EF) of the brain are the core skills critical for cognitive, social and physiological development (Diamond 2013). The most-reported EFs include planning and regulation (Vohs et al., 2014). Studies around Neuroimaging and Psychology have shown that different parts of the PFC are activated during each EF (Hughes, Power, O'Connor & Orlet Fisher, 2015); however, most of these studies have been subjective and have shown discrepancies in their findings (Murugan et al., 2017). We observe that the subjective nature of these studies is as a result of the limitations of the neuro-imaging tools used in most of these studies. These limitations make it easy for several interpretations to be drawn from these studies. Meanwhile, evidence exists that other parts of the larger brain are also implicated during executive functioning. This may be responsible for the uncertainties around studies focusing on just the PFC. A key interest of this study is inhibition; therefore, we elaborate on it below.

2.7.1 Inhibition

Inhibitory control (or inhibition), which is a core EF, is the cognitive ability required for behavioural regulation (Narayanan & Laubach, 2017; Ramos-Loyo, González-Garrido, García-Aguilar, & Del Río-Portilla, 2013; Stramaccia et al., 2015). Diamond (2013) also described inhibition as the ability to control one's attention, behaviour, thoughts and/or emotions to override a strong predisposition with the appropriate action.

Like other EFs, the PFC is activated during inhibition (Hughes et al. 2015; Goldstein & Volkow 2011); however, there appear to be conflicting views regarding parts of the PFC responsible for inhibitory responses (Murugan et al., 2017). Stramaccia and colleagues (2015) suggest that the dorsolateral prefrontal cortex (DLPFC) is responsible for these responses alongside the inferior frontal gyrus (IFG), while Narayanan and colleagues (2017) argues that the medial prefrontal cortex (MPFC) is more likely to be implicated.

We note that Inhibition, as reported by each of the studies referenced above, differs slightly in context and this may be partly responsible for the conflict in opinion regarding the part of the PFC implicated in the studies. Narayanan and Laubach (2017) considered inhibition from the functional anatomy and biological viewpoint. Although Narayanan and Laubach (2017)'s study clearly stated that the functional anatomy of inhibitory control is unclear, it suggests that inhibition, like other executive functions, is also mediated by the prefrontal cortex. Inhibition in Narayanan and Laubach (2017)'s study is described as the ability to wait and ultimately delay impulsive and premature responses; they argued that dysfunction in the medial prefrontal cortex alters this ability. Meanwhile, Stramaccia and colleagues (2015) considered inhibition from the behavioural viewpoint. They referred to inhibition as response stopping, which is the ability to outrightly stop an ongoing course of action. This study highlights the right inferior frontal gyrus (rIFG) as a common focus of attempts to modulate response stopping using non-invasive brain stimulation. However, it also posits that other cortical regions, especially the right dorsolateral prefrontal cortex (rDLPFC) have been implicated in inhibitory control. This argument is significant to this study as it highlights the involvement of the PFC, albeit the DLPFC in inhibitory control. The study also suggests that response stopping ability is often impaired in psychiatric conditions, which are characterised by impulsivity and poor inhibitory control. This ties well with our argument that inhibition is impaired in most known cognitive impairments. This argument is further strengthened by Honan and colleagues (2015) which was aimed at developing and piloting a new clinical measure of social disinhibition. In Honan and colleagues' study participants included 19 moderate-to-severe Traumatic Brain Injury (TBI) patients and 14 healthy controls. Participants viewed scenes of complex social situations and were asked to describe a character in them (Part A), describe a character while inhibiting inappropriate responses (Part B), and describe a character while not only inhibiting negative but also providing positive responses (Part C). Results show that both TBI individuals and the healthy controls were both negative in their responses to Part A, the TBI individuals were significantly impaired in Part B, and a trend towards TBI individuals being impaired in their ability to produce more socially accepted responses in Part C. Although this study attempts to contribute towards meeting the need for a well-validated clinical assessment capable of assessing social disinhibition deficits, we note that social interaction as represented in this study is focused on participants' observation of the scenes of complex social situations with minimal participation. We argue that although this study finds relevance in our domain of interest, participatory social scenarios may present a more formidable argument to the findings of this study. Participatory social scenario here refers to scenarios where all interacting parties are contributors (in the form of verbal and/or non-verbal cues) to the scenario. Moreover, we argue that the conflicts in opinions in implicated PFC regions are most likely consequent to the contexts, scenarios and approaches adopted by these studies.

Social Inhibition

Social inhibition refers to the ability to inhibit automatic response in favour of producing more socially acceptable responses (Honan, Skye, Fisher, & Osborne-Crowley, 2015; Honan et al, 2017; Denollet, 2013); Honan and colleagues (2015), discussed previously, associated social disinhibition (deficits to social inhibition) with traumatic brain injury (TBI); this is in-line with our argument that disinhibition is common in most known cognitive impairments. Inhibition has featured severally in social psychology studies within the social domain (Denollet, 2013; Yarczower & Daruns, 1982; Skarratt, Cole & Kingstone, 2010; Blascovich et al., 2002). These studies, however, differ in scope and domain. Denollet (2013) investigated social inhibition from interpersonal sensitivity (IS). Following previous studies on non-human primates and drawing inferences from those studies, the study suggests that social inhibition is a major determinant of chronic social stress in children. Although this does not directly relate to our research interest, it does highlight the significance of social inhibition in humans. Skarratt and colleagues (2010) presented a concept termed social inhibition of return. Skarratt and colleagues (2010) study defined inhibition of return (IOR) as an effect which represents the suppression of the response to stimuli that had previously been the focus of attention or existed in the same location. Social IOR (SOIR) as defined by this study is the IOR effect resulting from a prior performance by a confederate or conspecific at the location of interest. This study, however, argues that only a real conspecific can induce SIOR in another person, whereas an animated conspecific cannot. On the contrary, Blascovich and colleagues (2002) taking cues from Allport’s (1985) well-accepted social psychology study suggested that the behaviour of individuals can be influenced by the actual, imagined or implied presence of others. This questions the argument by Skarratt and colleagues (2010) about only real conspecifics being able to induce SIOR in another person. Our research does not investigate SIOR any further; however, the knowledge of its existence contributes to the evidence of social inhibition as an accepted construct both within and outside our area of interest. Moreover, it also justifies the use of non-human confederates in this study.

We see from the studies in the previous paragraph that the definition of social inhibition as a construct tends to take the shape of the context of consideration. Generally, the term social inhibition largely refers to inhibition (as an executive function) within the social domain.

Inhibition was represented by a slower response to stimuli in Skarratt and colleagues' (2010) IOR study, while social inhibition was accounted for by the slower response when participants perform a task knowing that another confederate had previously performed the same task in the same location. Social inhibition is often considered with social interaction (Blascovich et al., 2002).

Social interaction thrives when interacting parties consider the emotional states of each other (Steinbeis, 2016). Thriving social interaction as used here refers to an interaction between two or more parties where the interacting parties are willing to associate with each other in socially acceptable manners. Meanwhile, the Antisocial Behaviour act 2003 and the Police Reform and Social Responsibility Act 2011 defines anti-social behaviour as behaviour by a person which causes or is likely to cause, harassment, alarm or distress to a person not of the same household as the person. The degree to which an individual exhibits antisocial behaviour can be associated to personality and temperament (Romero et al., 2001); it can also be associated with mental health deficits (Miller et al., 1997). Blascovich and colleagues (2002) suggest that social and anti-social behaviour can only be exhibited (and indeed inhibited) by an individual when the individual perceives the social presence of another individual. Allport's (1985) study argued that social presence can either be actual, implied or imaginary. This well-accepted argument has formed the basis for several studies in this domain (Blascovich et al., 2002; Jones, 1998; Morawski, 2000). The concept of actual, implied or imaginary social presence also creates a relevant background for experimental social psychology. Blascovich and colleagues (2002) also contribute significantly to our study, especially because of its focus on Immersive Virtual Environments (IVE). Following Allport's (1985) argument, Blascovich and colleagues (2002) argued that social influence exerted by a representation of a confederate is largely dependent on the behavioural realism and social presence of the confederate. Behavioural realism here refers to the degree to which a representation of a confederate behaves like the actual confederate in the real world, while social presence refers to the degree to which he or she is in the presence and interacting with an actual confederate. Studies focusing on virtual humans fall into the implied social presence class (Bailenson, Blascovich, Beall, Loomis, & Environments, 2001). Social interaction is achievable when variables of a social presence scenario can trigger the right emotions (Bailenson et al., 2001). Bailenson (2001) and Steinbeis (2016) also linked emotion to social interaction. Following this, we expect increased activity within brain regions responsible for emotions during social interaction. This, however, is outside the scope of this work because it involves deeper brain regions than just the frontal lobe (Dahm et al., 2017), and will not be explored.

The neuro-imaging tools required to measure deeper brain regions are highly expensive and not readily available. However, this thesis is concerned with inhibition during social interaction, which evidence suggests may be accounted for within the PFC (Denckla, 1996; Koechlin & Summerfield, 2007). The PFC regions implicated during inhibition are discussed earlier in this section. A broad range of neuro-imaging tools exists (of which one is accessible by us) which can sufficiently measure neural activity within the PFC. As a result of limitations of these neuro-imaging tools, neural correlates of social inhibition and social interaction throughout this thesis are only limited to the PFC.

Emotion represents a large family of stimuli (Adolphs, 2017). The emotional state of individuals during social interaction affects the outcome of the entire interaction (Lozada, Halberstadt, Craig, Dennis, & Dunsmore, 2016). Dahm and colleagues (2017) argue that a conversation with a person that exhibits negative emotions is likely to trigger a negative response. Antisocial behaviours fall into a large family of negative emotions (Baglivio, Wolff, DeLisi, Vaughn, & Piquero, 2016), and therefore should be inhibited. Meanwhile, disinhibition is common in most known cognitive impairments, especially impairments resulting from frontal lobe damage (Fonseca et al., 2017) and has been widely studied using paradigms for evaluation of EFs. Disinhibition is defined as the failure to inhibit automatic responses in favour of producing required responses (Honan, Skye, Fisher & Osborne-Crowley, 2015). However, we are careful to assume that inhibition measured by these paradigms are the same as inhibition needed within the social domain. Therefore, this study shall also attempt to correlate inhibition within these domains.

2.7.2 Paradigms for Evaluating EFs

Several studies have widely adopted known paradigms to investigate executive dysfunction in human and non-human subjects, as well as to attempt improving cognitive functionality (Stroop, 1935). Executive dysfunction refers to the range of cognitive, behavioural and emotional difficulties that often occur after injury to the frontal lobes of the brain (Stuss, 2011).

A number of these paradigms exist and have also been widely adopted in clinical practice. We briefly discuss three of the most common ones: Stroop, Hayling, Simon and The Go/No Go Paradigms below.

Stroop Task

Stroop's task is one of the most widely explored tests of executive functions. Stroop (1935) demonstrated cognitive interference in relation to a reaction time due to a mismatch in stimuli. Stroop's study consists of three experiments:

In the first experiment, the effect of interfering colour stimuli upon reading names of colours serially was investigated. In this experiment, Stroop (1935) found that the difference in the time for reading the words printed in colours and the same words printed in black is the measure of the interference of colour stimuli upon reading words. Also, the difference in the time for naming the colours in which the words are printed, and the same colours printed in squares (or swastikas) is the measure of the interference of conflicting word stimuli upon naming colours.

In the second experiment, the effect of interfering word stimuli upon naming colours serially was investigated while participants read 100 words. In this experiment, Stroop (1935) found that the interference of conflicting colour stimuli upon the time for reading 100 words caused an increase of only 2.3 seconds or 5.6 per cent over the normal time for reading the same words printed in black. Stroop (1935) suggests this increase is not reliable. But the interference of conflicting word stimuli upon the time for naming 100 colours caused an increase of 47.0 seconds or 74.3 per cent of the normal time for naming colours printed in squares.

In the third experiment, the effect of practice on interference was investigated. Here, Stroop (1935) found that practice was found either to increase or to decrease the variability of the group depending upon the nature of the material used. Meanwhile, there was an indication that the gender of participants could impact this activity.

Hayling Task

Key References: Burgess and Shallice (1997); Bielak, Mansueti, Strauss and Dixon, (2006); Nathaniel-James, Fletcher, and Frith (1997)

The Hayling Task has been historically applied in studies on verbal initiation and suppression (Nathaniel-James, Fletcher, & Frith, 1997). The Hayling task does measure response inhibition and other cognitive abilities such as executive functions and working memory capacity (Stenbäck, Hällgren, & Larsby, 2016).

The Hayling Sentence Completion Test evaluates one's ability to inhibit an automatic response (Pérez-Pérez et al., 2016). The Test was developed by Burgess and Shallice in 1997 (Burgess & Shallice, 1997; Bielak, Mansueti, Strauss, & Dixon, 2006). Each of two sections of the original Hayling test consists of fifteen sentences, each missing the last word. In the first section, participants are required to complete each sentence with a sensible word; here, the initiation speed is measured. In the second section, participants are required to complete each sentence with a non-sense word; here, the inhibition to sensible words in measured.

The skills of verbal initiation and suppression are required in verbal fluency tasks (Nathaniel-James, Fletcher, & Frith, 1997). Nathaniel-James, Fletcher and Frith (1997) adopted the Hayling sentence completion task to investigate cortical regions implicated during verbal initiation and the regions activated during verbal suppression. Nathaniel-James et al. (1997) study provide details on the implementation of the Hayling task, moreover, it is significant to this PhD as it adopted a neuro-imaging tool, the positron emission tomography (PET). However, the neuro-imaging tool adopted by Nathaniel-James et al. (1997) is not available for this PhD. Nathaniel-James et al. (1997) suggested that response initiation was associated with the left-sided activation of the frontal operculum, inferior frontal gyrus, middle temporal gyrus and the right anterior cingulate gyrus, while response suppression was associated with the left frontal operculum, inferior frontal gyrus and the right anterior cingulate gyrus. These regions are outside the regions measurable by the fNIRS, therefore whilst the methods find useful application with administering the Hayling task, the findings are not directly useful to the PhD. The Hayling task finds useful application in clinical studies targeting frontal lobe lesions (Bielak, Mansueti, Strauss, & Dixon, 2006; Pérez-Pérez et al., 2016).

Simon Paradigm

The Simon paradigm evaluates the spatial origin of stimuli and their corresponding responses (Hommel, 1993). According to Hommel (1993), the Simon effect indicates that choice reactions can be performed more quickly if the response corresponds spatially to the stimulus. Like the Stroop task, the Simon task is a well-studied behavioural paradigm of attentional selection (Liu, Banich, Jacobson, & Tanabe, 2004). Liu et al. (2004) compared the neural mechanisms of attentional control involved in the Simon task to a special kind of Stroop task called the Spatial Stroop Task; they argue that the brain areas significantly more activated during the Simon task were those areas sensitive to detection of response conflict, response selection and planning (anterior cingulate cortex, supplementary motor areas, and precuneus). In contrast, the regions significantly activated during the Stroop task were those responsible for biasing the processing towards the task-relevant attribute (inferior parietal cortex).

The Simon paradigm is a result of a 1967 Study by Simon and Rudell. Simon and Rudell (1967) investigated Reaction Time (RT) to monaurally presented verbal commands and argued that the speed of processing a symbolic content of command was affected by the ear in which the command was heard. Taking cues from this, Liu et al. (2014) further defined the Simon effect as the interference people experience when there is a stimulus-response conflict.

A special kind of paradigm referred to as the Social Simon Effect (SSE) occurs when two participants share a Simon task by making a Go/No Go response of one of two stimulus features (Sebanz, Knoblich, & Prinz, 2003; Vlainic, Liepelt, Colzato, Prinz, & Hommel, 2009). Sebanz et al. (2003) argue that the Simon effect occurs when two participants perform this version of the Simon task together but disappear when participants perform the task separately. They attributed the SSE to the automatic co-representation of the co-actor's actions. Vlainic et al. (2009) however argue that the SSE can also be felt with just prior offline information about a co-actor’s presence.

The Simon Social task sufficiently measures inhibition (Vlainic, Liepelt et al. 2009). However, we argue that the inhibition generated from the Simon task is not as a result of the presence of a confederate, but a result of the spatial interference. This, therefore, limits the relevance of the Simon task to our study.

In summary, the highlighted paradigms have featured in past studies aimed at evaluating inhibitory responses during task performance (Y. Song & Hakoda, 2015). These paradigms include Most frequently adopted are: The Stroop paradigm, The Simon Paradigm, the Go/No Go Paradigm, Face in the crowd paradigm and the Hayling Test (Honan et al., 2015).

However, we observe that these paradigms either evoke inhibition without showing a need for confederates or are not suitable for naturalistic social interaction; consequently, they are not at the core of this research. The Hayling sentence completion task is however explored within the studies.

2.8 Summary of Theoretical Framework

Several theories were considered during this research; however, the theoretical framework of this research is based on four of these theories. These include Theory of inhibition, Theory of emotional regulation, Theory of mind and Miller and Cohen’s model. Other theoretical frameworks and models were also found which include Miyake and Friedman’s model and

Lezak's conceptual model. These models helped our understanding of concepts and existing knowledge relating to this research. While some of these theories were directly related to the goal of this research, others were either not directly related, or had been adapted to fit studies where they have featured. We eventually settled for the four theories highlighted above because of their direct relevance to the aim of the PhD. Meanwhile, previous examiners advised the adoption of the theories we settled for.

Theory of Inhibition: This theory assumes that participants undergo two latent states of attention and distraction during any mental task. It also suggests that inhibition increases during attention but decreases during distraction (Kimble, 1949; Smit & vanderVen, 1995). Conversations are one of such mental tasks and participants are expected to undergo these latent states (which are completely imperceptible to them). Following this theory, we argue that inhibition is inherent in the state of attention in this mental task and is a key executive function required to effectively hold a conversation. Furthermore, we argue that the neural basis of conversations will show indications of inhibitory response.

Theory of emotional regulation: This theory is based on the assumption that humans have a wide range of emotions and an ability to respond to ongoing demands of experience with this range of emotions in a manner that is socially tolerable and sufficiently flexible to permit spontaneous reactions as well as delay it if necessary (Gillespie & Beech, 2016). failure to regulate emotions has been linked with anti-social behaviour (Grandey, 2000), hence its direct relationship with this research. Emotional regulation theory is linked with response suppression and reappraisal during cognitive processes (Goldin, McRae, Ramel, & Gross, 2008).

Theory of mind: This theory is based on the assumption that humans can explain and predict other people's behaviour by attributing them to independent mental states (Gallagher & Frith, 2003). It is generally described as the ability to attribute mental states to oneself and others, and to understand that others have mental states different from one's own (Gweon, Saxe, & neuroscience, 2013). Theory of mind is linked with empathy and both are important processes in social cognition (Völlm et al., 2006).

Miller and Cohen's model: This theoretical framework, like most other executive function models (Denckla, 1996; Koechlin & Summerfield, 2007) suggests that the PFC plays an essential role in executive functioning (E. K. Miller & Cohen, 2001; Tirapu-Ustarroz et al., 2008). Our study is primarily interested in neural correlates indicative of inhibition which is a core executive function, therefore this framework is highly instrumental to the formation of this research.

	MPFC	DLPFC	Others	Ref
Theory of Inhibition	Yes	Yes	Left-inferior-frontal-gyrus (lIFG), left-middle-frontal-gyrus (lMFG), ventromedial prefrontal cortex (VMPFC)	(Houdé & Borst, 2015)
Emotional Regulation	Yes	Yes	The ventromedial prefrontal cortex (VMPFC), anterior cingulate cortex	(Etkin, Büchel, & Gross, 2015)
Theory of Mind	Yes	No	Cortical midline structures (CMS) which include adjacent rostral anterior cingulate cortex (rACC), medial posterior parietal cortices (MPPC), superior temporal gyrus, lateral orbitofrontal cortex, middle frontal gyrus, cuneus, the bilateral temporal-parietal junction (TPJ), the paracingulate, anterior and posterior cingulate and amygdala.	(Gallagher & Frith, 2003) (Mahy, Moses, & Pfeifer, 2014) (Völlm et al., 2006)

Table 1 Neural Basis of Theoretical Frameworks

The evidence available to us is summarised in Table 1. The neural basis for the theories is investigated and the brain regions implicated in previous studies are captured. Our interest is in the medial prefrontal cortex (MPFC) and the dorsolateral prefrontal cortex (DLPFC), therefore we assign a Yes to either of these regions if they have been implicated by any previous study and a No if otherwise. Other regions within the PFC (capturable using the fNIRS) are also investigated during data analysis. Miller and Cohen's model has not been captured in the table above because it fundamentally suggests the heavy involvement of the entire PFC in cognitive control.

2.9 Summary of findings

Several studies have used virtual reality (VR) simulations to evoke neural responses to controllable stimuli to study the neural basis. Several other studies have also attempted to investigate virtual humans and social interaction, but only a few of these studies have attempted to investigate the neural correlates during these interactions. Moreover, these studies have mostly targeted passive interactions and observatory perspectives of interactions (Schilbach et al., 2016; Slater et al., 2013; Hari, Henriksson, Malinen, & Parkkonen, 2015). Passive interactions and observatory perspectives here refers to interactions where participants are either not directly involved in the interaction, interactions are based on observation of the interaction between other parties or interaction is based only on cues displayed by the confederate. During literature review, no study was found which attempts to investigate the neural correlates of social interaction in humans actively engaging in conversations with virtual humans. The veracity of this claim is further strengthened by Hari et al (2015) and Schilbach and colleagues (2015). Hari and colleagues (2015) in their study which was aimed at highlighting the centrality of social interaction in the human brain function suggested that research on the brain basis of social interaction are mostly centred around passive spectator science. They further suggested a move towards studies that engaged participants while simultaneously recording the brain activities of the interacting persons. Hari and colleagues (2015) study provide a clear definition of active engagement as used in this study which refers to a combination of verbal and non-verbal cues between two or more parties, like real-life daily conversations. Schilbach (2016) described earlier also included a recording of participants' brain activity, however, this study failed to create scenarios for active engagement of participants as suggested by Hari and colleagues (2015); this research attempts to fill this gap.

Three studies investigating the neural correlates of social interaction in humans as they converse with friendly and unfriendly virtual human confederates were carried out towards achieving this. Meanwhile, this research set out to investigate inhibition as it applies to social interaction, therefore the neural basis emanating from these studies are investigated from the inhibitory response point of view.

The social nature of humans requires regular interaction with the environment (Goudie, 2018). While some components of this environment are animate and require active interaction, other components are inanimate and can only be passively interacted with. Human to human interaction is the most common of the former (He & Han, 2006; Knapp, Hall, & Horgan, 2013).

However, we know form mental health studies that social interaction tends to thrive in individuals with no diagnosis of cognitive impairments (Gallagher & Frith, 2003)

The National Health Service Survey suggests that one in six people in the UK experience a mental health problem (Mcmanus, Bebbington, Jenkins, & Brugha, 2016). This accounts for the increased research interest in mental health and related studies. Anti-social behaviour is strongly associated with several mental illnesses such as post-traumatic stress disorder (PTSD) (Booth-Kewley, Larson, Highfill-McRoy, Garland, & Gaskin, 2010), hence our interest.

Diamond (2013) defines Inhibitory Response (IR) (or inhibition) as an executive function aimed at suppressing a natural reaction. The mechanisms behind inhibition and emotional control are often argued to overlap (Bartholomew, Heller & Miller, 2019). Bartholomew and colleagues (2019) while evaluating relationships among constructs of inhibitory control, emotion inhibition and emotional regulation argued in line with a previous study by Joormann and Gotlib (2010) which suggest that inhibitory control supports successful emotional regulation. In neural terms, IR refers to activation within the prefrontal cortex (PFC) quelling that within the amygdala (Quirk, Likhtik, Pelletier, & Paré, 2003). IR has been evoked in previous studies by adapting one or more of the Stroop task (Stroop, 1935), Simon task (Hommel, 1993), Hayling task (Nathaniel-James, Fletcher, & Frith, 1997), face in the crowd paradigm (Pinkham, Griffin, Baron, Sasson, & Gur, 2010). It is also featured in studies investigating fear response (Wendt et al., 2015). Fear response refers to the body's reaction to a perception of danger which can vary from mild cases of fear-potentiated startles (Wendt et al., 2015), to confronting (fight) to avoiding (flight) the perceived danger or even freeze responses in extreme cases of horror (Jansen et al. 1995). While Jansen and colleagues argued that these responses are regulated by a common set of brain neurons, Wendt and colleagues (2015) linked them to the amygdala. Although Aleksandra Landowska's study (within the group) was primarily concerned with inhibitory response within the PFC to virtual heights, the study also considered fear response when participants are exposed to these virtual heights in an immersive virtual environment. Our literature review on the prefrontal cortex (in the previous chapter) shows that several studies (Farrell, Holland, Shansky, & Brenhouse, 2016; Jiang, Bailey, Xiang, Zhang, & Zhang, 2016; Song & Hakoda, 2015) have also attempted to show the parts of the PFC activated during inhibitory response in the context of these activities. However, our literature review has not revealed the investigation of neural responses attributable to inhibition within the brain during social interaction. One of the possible reasons for this is the difficulty in tying social interaction to block tasks as is common in most neuroimaging studies (Lee, Preissl, Enck, & motility, 2017). Block tasks in neuro-imaging contexts are tasks broken into fixed timeslots and analysed in block segments.

Slater and colleagues (2013) investigated bystander responses to a violent incident in immersive virtual reality. Slater and colleagues (2013) study investigated the conditions under which a bystander will intervene to try to stop a violent attack by one person on another as it is generally believed that the greater the crowd, the less the chance that any of them will intervene. They also investigated the complementary model which suggests that all other things being equal, the bystander is more likely to respond if they share a common social identity with the victim. This was demonstrated in immersive virtual reality using 40 male supporters of Arsenal Football Club (AFC) in a two-factor-between-groups experiment. The victim was either an AFC supporter or not. The participants were more likely to intervene when the victim was an AFC supporter, therefore the study lends support to the social identity explanation. This suggests that VR generated stimuli can be responded to in a similar way to real-life generated stimuli. This argument is further strengthened by body ownership illusion studies in immersive virtual environments (IVE) (Kilteni, Bergstron & Slater, 2013) and related neuro-imaging studies (Schilbach et al., 2006). VR has also shown potential in exposure therapy especially with clinical-rated PTSD (Rothbaum, Hodges, Ready, Graap & Alarcon, 2001). Although these studies suggest growing evidence for some behavioural similarities between how humans respond to VR generated stimuli on one hand and real-life stimuli, on the other hand, the situations under which these similarities have been tested are very restricted to date, focusing majorly on exposure therapy, bystander intervention and body ownership illusions. A more comprehensive body of research is needed across different scenarios to fully map overlap and differences between real life and VR generated stimuli. A recent work within the group by Aleksandra Landowska has measured indication within the PFC of inhibitory response to virtual stimuli. This combined highly immersive virtual reality Cave Automatic Virtual Environment (CAVE), the Octave with the functional near infrared spectroscopy (fNIRS). However, this work did not investigate any social inhibitory component. Furthermore, it neither used virtual humans or a display system practical for clinical or home use.

Aleksandra Landowska’s final study adopted a CAVE; whilst much of the assumptions of this research are built around Aleksandra’s research, the immobility of the CAVE limits its applicability to home use. Schilbach and colleagues (2006), which is also influential to this PhD, adopted a desktop VR system which has an advantage in terms of mobility; however, compared to more conventional Immersive Virtual Reality Systems (IVRS), the immersivity of desktop VR systems has been questioned in previous studies (Lorenzo, Lledó, Pomares, Roig, & Education, 2016); especially because users are not completely immersed in these systems. This PhD initially targeted an immersive display, with home and possible clinical use at the core of its requirement. The immersivity requirement of our proposed system and the questions surrounding the immersivity of the VR desktop systems (Lorenzo, Lledó, Pomares, Roig, & Education, 2016) suggested the need for a head-mounted display (HMD). No previous study has adopted an HMD for neuro-imaging studies. This may be due to an observed pattern with popular HMD designs which may not allow for combination with any other head-mounted wearable device. This research adapted an HMD to allow for a wearable neuro-imaging device initially. This adaptation was achieved by breaking the upper regions of the HMD and attaching foams to the broken edge for safety. Breaking the upper region allowed space for the head-mounted display to be worn alongside a neuro-imaging tool. Data analysis initially suggested a high data exclusion rate; consequently, it further adopted a large display screen and subsequently a combined projector system (the immersive suite) to alleviate this problem. This presented an opportunity to investigate the perception of virtual humans across three distinct display systems.

Virtual humans are capable of triggering emotional responses in humans (Schilbach et al., 2006; Slater et al., 2013) and measurable neural correlates exist for these responses (Peelle, 2019; Schilbach et al., 2006b). Virtual humans, like most virtual reality components, also bring the advantage of repeatability (Osterlund & Lawrence, 2012; Piron, Cennis, Tonins, & Dam, 2001; Saleh et al., 2013), and present a cheaper option when compared to the cost of recruiting trained actors as real human confederates. They also find useful application in health education and therapies targeting cognitive behaviour (Kenny, Parsons, Gratch, Leuski, & Rizzo, 2007; KISS, Benedek, SZIJART, & Care, 2004). A possible alternative to virtual humans in research is mannequins. Responsive mannequins are increasingly being installed in Nursing schools, one of which is the University of Salford School of Nursing and Midwifery, Mary Seacole Building. These mannequins respond to stimuli and are able to evoke emotions, but they are currently unable to engage in verbal conversations. Our interest is in a VR system; therefore, virtual humans in virtual environments are best suited for this research.

As mentioned earlier, studies targeting virtual humans and social interaction have targeted observatory aspects of interaction. Schilbach and colleagues (2006) investigated the neural basis of interaction with virtual humans. In their fMRI study, participants were tasked with reporting how involved they felt in a conversation with a virtual human based on the gaze position of the virtual human. This study did not incorporate any verbal cue. We argue that the neural basis of observatory conversation may differ evidently from the neural basis of active social interaction. We, therefore, attempt to tie empirical evidence to this argument. Meanwhile, Schilbach et al. (2006) used an MRI while our research uses the functional near infrared spectroscopy (fNIRS) which is a non-invasive neuro-imaging tool that measures neural activity only within the prefrontal cortex (PFC). As a result of the frontal lobe limitation of the fNIRS, the findings from this research are limited to the PFC.

Social interaction is a naturalistic activity, and the fNIRS, as well as the electroencephalogram (EEG), are suitable for this activity because of their portability and real-time data capture during usage. Unlike the fMRI where naturalistic movement is not possible and neural correlates are only investigated at the end of an activity block, the fNIRS and EEG allow for natural movement and gestures which are fundamental to active conversations within the context of this research. Meanwhile, the fNIRS offers better spatial resolution than the EEG (Yin et al., 2015) and based on this, we argue that the fNIRS is a better tool for this purpose than the EEG. All three studies used the fNIRS for neuroimaging, display medium was modified as the need arose. Meanwhile, studies targeting the neural basis of non-observatory social interaction have mostly considered gaze-based interaction (Hari, Henriksson, Malinen, & Parkkonen, 2015; Schilbach et al., 2006). This kind of interaction could easily be broken down into blocks of equal time ranges for neuro-imaging analysis as is common with neuro-imaging studies. This is not easily feasible with more natural interaction which has the verbal and non-verbal components.

2.10 Conclusion

Immersive VR presents a means to generate desired stimuli in human subjects. From our observation, however, not many works of literature have attempted to combine VR with neuroimaging with the aim of evaluating and measuring neural responses especially within the social domain. Schilbach (2016) described within the literature under section 2.3.1 being the most significant of these studies. We shall therefore attempt to combine these disciplines to bridge this gap in this research.

The functional near infrared spectroscopy (fNIRS) is proposed for neuroimaging. This choice is justified by Aleksandra Landowska’s research (Landowska, Roberts, Eachus, & Barrett, 2018), within the group. Aleksandra’s study shows that fNIRS is effective in measuring PFC activity.

The paradigms for assessing inhibition highlighted in this review either show considerable measures of inhibition at certain points or throughout the experiments. They have also been used widely in the evaluation of executive functions (Dalton, Sciadas, & Nantel, 2016; Hovik, Plessen, Skogli, Andersen, & Øie, 2013). However, the stimuli in these paradigms are triggered by the inherent tasks. Our interest is in triggering these stimuli through social interaction with virtual human confederates and investigating neural response indicative of inhibition. Meanwhile, Honan and colleagues (2015) argue that the inhibition evaluated by the tests of inhibition discussed above may differ from inhibition within the social domain. We, therefore, seek to correlate the outcome of one of these tests with the neural response evoked in our experiment.

We propose an experiment in which these confederates can trigger a neural response in our test subjects by displaying adequate non-verbal and verbal cues.

CHAPTER 3

METHODOLOGY

3.0 Introduction

This chapter details the PhD journey, the approaches and procedures adopted during the research. We discuss the aim, goals, processes through which we arrived at the research questions and the rationale behind the research.

We present an overview of the studies carried out during the research, the goals of the studies and the build-up to each. We also highlight approaches that were considered or attempted but eventually excluded from the PhD.

The chapter is split into two parts. The first part details the approach to the PhD and experimental design methodology, while the second part details the system design methodology.

3.1 Point of Departure

3.1.1 The Group

At the start of the PhD, the group was headed by the supervisor, Professor David Roberts, a Professor of Telepresence who has widely explored virtual environments and display systems. Professor Roberts had students both in the school of computing and psychology. Within the Team was also the co-supervisor, Dr Peter Eachus, who is the head of Psychology at the University of Salford. Other members of the group include Dr Aleksandra Landowska and Dr John O’Hare who have recently rounded up their PhD. Dr Landowska has a neural science background with interest in the neural basis of exposure therapy, while Dr John O’Hare has a computer science background, with vast experience working as a technician overseeing the virtual reality Cave Automatic Virtual Environment (CAVE), the Octave at the University of Salford. Dr Alan Fairchild, from computer science who graduated within the first year of this PhD. Meanwhile, Sam Royle who is a PhD student (co-supervised by Professor David Roberts) and doubles as the technician of the school of psychology. Sam Royle has a psychology background and is interested in addiction. Finally, Andrew Hodrien (also co-supervised by Professor David Roberts) has a psychology background, but his research investigates amputees and body ownership. Beyond the PhD, Andrew Hodrien also has an interest in lucid dreams and out of body experience.

A few similar research works within the group include:

- Measuring prefrontal cortex response to virtual reality exposure therapy in freely moving participants by Aleksandra Landowska
- Telethrone by Allen Fairchild and John O'Hare
- Neural basis of virtual reality exposure treatment by Aleksandra Landowska
- Bringing the client and therapist together in virtual reality telepresence exposure therapy by David Roberts and Allen Fairchild

As a result of the diverse backgrounds of group members, the research considers concepts from diverse viewpoints. Diverse viewpoints here refer to what was known (from previous studies) in the different areas at the start of the PhD.

3.1.2 The Researcher

The researcher has come from a computer science background. Most of what was known to the researcher at the start of the PhD has its background from computer science and methods peculiar to this discipline. The researcher's bachelor's degree was in computer science and Master's in Databases and Web-Based Systems, which at surface level do not share any similarities with the PhD. However, the researcher's MSc dissertation was part of an EPSRC funded pilot project, targeting mild cognitive impairments and involving three universities: the University of Salford, the University of Manchester and the University of Lancaster. As part of the dissertation, the researcher was required to implement a high-level user interface (involving chatbots) which receives data mining outcomes of keyboard and mouse activity from participants/users as input and refers them for medical help if needed. This was based on the knowledge that mild cognitive impairments such as Alzheimer's disease can only be better managed if detected early in its process. This pilot study represents an introduction to mental deficits for the researcher. Although the researcher's contribution to the EPSRC project was the implementation of a chatbot which held a conversation with users based on keywords and referred them to where they could get help if they have had previous episodes of forgetfulness or memory losses, the researcher was able to identify the need for more studies in the area of social interaction albeit from the human-computer interaction (HCI) point of view. Meanwhile, the researcher had taken a module on virtual reality (VR) during the MSc and picked interest in this discipline.

Coming into this PhD, the researcher saw a possible link between VR and conversational agents and their possible application to cognitive impairments and mental deficits. This was refined within the group to tie well with studies within the group at the time as well as available resources.

3.1.3 What was known

A brief literature review was embarked on within the first three months of the PhD. The direction of the initial literature review was influenced by regular meetings with Professor David Roberts, Aleksandra Landowska and Sam Royle. Prior understanding from the MSc dissertation also contributed.

Within the first three months,

- Brief literature survey suggested that the brain responds to VR generated stimuli as if they were real (Hoffman et al., 2004; Baumgartner et al., 2008; Campbell et al., 2009). However, we did not find many studies that had investigated neural responses to VR to strongly back up this claim. One of the few resources that were helpful within this period was the virtual human toolkit developed at the University of South Carolina (USC). This toolkit was considered a viable option for creating our virtual humans at the start of the PhD but was discarded as a result of the limited configurability of the virtual human toolkit characters.
- The fNIRS, which was the only neuro-imaging tool available at the start of the PhD is only capable of investigating neural activity within the frontal lobe, which includes the prefrontal cortex (PFC) (Ferrari & Quaresima, 2012). However, the fNIRS has better spatial resolution than the EEG and better temporal resolution than the fMRI which are other popular neuro-imaging tools (Yin et al., 2015). The fNIRS also allows for unrestricted movement and integration with a wide range of displays.
- Executive functions, which includes inhibition is highly accounted for within the prefrontal cortex (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Tirapu-Ustarroz, Garcia-Molina, Luna-Lario, Roig-Rovira, & Pelegrin-Valero, 2008).
- Paradigms exist such as Stroop, Hayling, Simon and Go-No-Go which are effective for evaluating inhibition and other executive functions (Collette et al., 2001).

- Combining most virtual reality head-mounted displays in their original form with the fNIRS was practically impossible as it had been attempted within the group by Aleksandra Landowska and Sam Royle. This is because commercial HMDs were designed to completely cover users’ heads to make them more comfortable and adjustable for users. Neuroimaging tools, on the other hand, are also mostly designed to be worn on users’ heads. Combining these devices and getting desired results were indeed seemingly impossible without any form of adaptation. Therefore, the feasibility of modifying a commercial HMD was prioritised.

3.1.4 Relevance of research

While the literature review was necessary for identifying gaps in the field of research, the relevance of the research to a real-life application was also investigated and was useful in designing the system. Before the start of the PhD, contacts had already been established with Dr Anthony Hodgson of the Dementia Clinical Research Delivery, Salford Royal Hospital and also with the Brain and Spinal Injury Center (BASIC), Salford. These contacts (especially Dr Anthony Hodgson) affirmed the relevance of the research and further offered suggestions based on clinical experience. They also highlighted possible challenges especially with the recruitment of unhealthy participants should that be needed in the course of the PhD.

This research has also been demonstrated in so many events and exhibitions including the Manchester Science Festival, the BrainBox event, a VR exhibition at the Manchester Metropolitan University as well as conferences. On one occasion the research caught the attention of a BBC reporter and was one of the projects discussed by Professor David Roberts on a BBC One show. It also featured in the 2017 version of the University magazine, the Salfordian.

In the second year of the research, Dr Alan Barrett, a consultant clinical psychologist at Pennine Acute Care Trust came on board and picked interest in the research. Dr Alan Barrett is also a Clinical Lead for the Military Veterans’ Service and Manchester Resilience Hub (adults). Not only has he been to the University to see demonstrations of our system, but he has also brought in a team of consultants for this purpose. Dr Alan Barrett and his team find this research relevant with sufferers of post-traumatic stress disorder (PTSD). Enquiries and applications for grants are ongoing with Pennine Acute Care Trust to make the system more clinically viable and investigate participants outside our ethically approved sets of participants.

3.2 Summary of Literature Review

The literature review aimed to help refine the research question, investigate already existing studies relevant to answering our research question, identify gaps and subsequently make informed decisions as regards the methods best suited to answering the research questions. An initial literature review was carried out at the start of the PhD which is represented in the Point of Departure section, subsequent reviews built on these, and they (the initial works of literature) also remained valuable throughout the research. Literature review for this research intersected the disciplines of virtual reality, psychology and neural sciences. Specifically, we focused on virtual reality display systems, virtual humans, social cognition, mental deficits, executive functioning, inhibition, the prefrontal cortex (PFC) and neuroimaging.

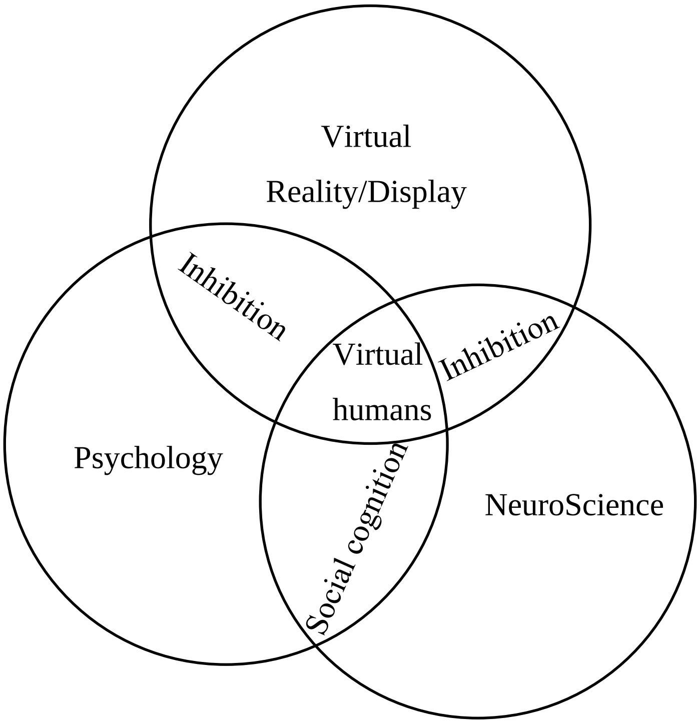


Figure 1 Theoretical Framework for Literature Review

Literature Review was based around the field of virtual reality (VR), psychology and neural sciences. Intersections between these fields were identified from previous studies as shown in Figure 1.

Virtual Reality: Focus was on studies that have attempted to show evidence that suggest that VR can be perceived as real life as well as evidence that suggest otherwise. Works of literature on VR display systems were also investigated. One of the goals of this research was to develop a portable VR system that could be adopted for home and clinical purposes, therefore studies that have adopted portable head-mounted displays were investigated. The major VR interest in this study was virtual humans, therefore we extensively considered virtual human studies. Virtual humans feature largely in human-computer interaction (HCI), especially conversational agents (Cassell, Sullivan, Churchill, & Prevost, 2000; Thiebaux, Marsella, Marshall, & Kallmann, 2008); however, in line with the aim of this research, we considered them with respect to triggering neural responses. This intersects with the two other major fields of the research; therefore, virtual human studies were investigated in line with their application in psychology and neuroscience.

Neuroscience: the focus was on existing neuro-imaging tools with an outlook on tools better suited to our aim and justification for adopting the neuro-imaging tool available to this research. We reviewed studies that have adopted various neuro-imaging tools especially in investigating cognition. We specifically considered studies that have looked at the neural basis of social cognition. The objectives here were to investigate if virtual humans within an immersive display are capable of triggering measurable neural response in humans during conversations, if these responses are indicative of inhibition and identify regions of the brain implicated during these conversations. This goal captures the intersection between these two broad fields as captured in Figure 1. Meanwhile, there are studies and theories within psychology that suggest the implication of specific brain regions during cognitive activities (Aron, 2007; Thomas et al., 2000). Although varying opinions exist as captured in these studies and their findings, we see an intersection between neural sciences and psychology in the areas of social cognition. Although only a few studies have combined virtual humans and neuroimaging, these studies have approached these disciplines from a psychological viewpoint, therefore, an intersection between these fields.

Psychology: We identified theories that tie well with our research interest. These theories are discussed subsequently. Studies on verbal and non-verbal communication were also reviewed as this is key to cognition and implementation of virtual humans (Kang, Gratch, & Worlds, 2010; Salem & Earle, 2000). Meanwhile, a research work by Aleksandra Landowska, within the group examined inhibition and fear response within a virtual reality (VR) CAVE. Although this has not been widely explored, the number of studies utilising VR within psychology reveals an increasingly popular intersection between these fields. However, in streamlining our investigation of this intersection to suit our research interest, we consider studies in this area focusing on virtual humans and their cues (verbal and non-verbal).

Literature review commenced at the start of the PhD to identify gaps in the area of interest, although these works of literature were updated as the PhD proceeded, some of these them remained relevant to the research even though there have been some advancements in the fields

3.3 Rational

The National Health Service Survey suggests that one in six people in the UK experience a mental health problem (Mcmanus, Bebbington, Jenkins, & Brugha, 2016). This creates a need for increased studies on mental health and associated therapies. dependant variables were *activation* and early stages of mental health deficits associated with the frontal lobe with disinhibition (Chelune, Ferguson, Koon & Dickey, 1986; Niki, Maruyama, Muragaki & Kumada, 2009; Honan, Skye, Fisher & Osborne-Crowley, 2015). As one of the core executive function, inhibition (and disinhibition) continues to be widely explored. Paradigms such as the Hayling Task, the Stroop task, Simon Task and the likes have been used to investigate inhibition and this makes available a wide range of evidence on inhibition and its implication in psychology. Inhibition in virtual environments has not been explored as much. Of the limited studies that have explored inhibition in virtual environments, Schilbach (2006, 2016) showed that neural correlates of social interaction with virtual humans can be investigated. Landowska et al (2018), a study within our group also showed that neural response indicative of inhibition can be measured in an immersive virtual reality display. Although these studies were carried out using different neuroimaging tools [fMRI for Schilbach et al (2006) and fNIRS for Landowska et al (2018)] the findings from these studies are majorly accounted for in terms of PFC response. This suggests the viability of PFC data in reporting the outcome of similar studies. This argument does not downplay the need for investigating neural correlates within deeper brain regions such as the amygdala, however, the neuro-imaging tools required to investigate these brain regions are characterised by restrictions in movement. The fNIRS as adopted by Landowska et al (2018) allowed for free movement of participants while their neural responses were being measured in real-time. The findings from this study tied well with previous studies and further highlighted the suitability of the fNIRS for our research. Schilbach (2006, 2016) and Landowska (2018) are highly influential and form the basis for the current research. Combining the lessons from above-mentioned studies increases the suitability of this research for therapies which is a huge potential application of this research.

Although inhibition has been widely investigated through paradigms targeting inhibition and executive functions in general, our literature review suggests a lack of consensus on the PFC region responsible for inhibition. Inhibition is reportedly accounted for within the dorsolateral prefrontal cortex (DLPFC) (Stramaccia et al., 2015) and the medial prefrontal cortex (MPFC) (Narayanan et al., 2017). The DLPFC and MPFC also play crucial roles in other cognitive activity including working memory (Euston, 2012) and decision making in social interaction (Rilling, 2009). The MPFC has been argued to be part of the brain regions referred to as the social brain (Grossmann, 2019), this further creates an imperative to investigate the MPFC alongside the DLPFC which appears to be more frequently associated with inhibition.

Although the presence of conversing parties during social interaction can be actual, implied or imagined (Allport, 1985), this study focuses on the actual presence of confederates and in particular, face-to-face conversation. However, creating real-life social interaction experiments to capture face to face conversation presents several challenges. Initial discussions at this stage suggested a bottleneck around obtaining ethical approval for this sort of experiment, especially with the possibility of participants being emotionally triggered. Meanwhile, the repeatability of the experiment becomes increasingly difficult to achieve when real humans are used. Also, the tendency of fatigue to set in with real humans is quite high; this also contributes to the issues of repeatability. To alleviate this problem, a possible option is to recruit trained actors as human confederates in this experiment; however, recruiting trained actors for this process is also not cheap. These issues justified the adoption of virtual humans and VR. The need for consistency with these variables is further exaggerated by the potential application of this and similar experiments in therapy, assessment and training.

VR brings the advantage of creating simulations that focus only on the desired stimuli. Meanwhile, theories such as the theory of inhibition suggest that inhibition is inherent in all cognitive activities and this is adequately accounted for within the prefrontal cortex (PFC). Moreover, the theory of emotional regulation suggests the suppression of emotional states during social interaction (Goldin, McRae, Ramel, & Gross, 2008). Although emotional regulation and inhibition have not been directly defined as the same cognitive process in literatures, Bartholomew and colleagues (2019) argued that inhibitory control supports successful emotional regulation. Moreover, overlapping mechanisms are reported between inhibition, inhibitory control and emotional regulation (Bartholomew et al., 2019), this suggests a significant involvement of inhibition and inhibitory control in social interaction vis-à-vis emotional regulation, hence our focus on inhibition. We note however that significant outcomes are possible in other brain regions outside of the PFC and other parts of the PFC not reportedly directly involved in inhibition. Whilst we are unable to capture deeper brain regions, any outcomes within the PFC shall be reported accordingly.

Virtual humans have also featured largely in human-computer interaction (HCI) and virtual reality (VR) studies. Although the perception of virtual humans has been widely explored, combining virtual humans and neuroimaging is not as popular. A few studies, however, have attempted to combine them, and their findings have suggested similarities with previous knowledge with real humans in social cognition (Amodio & Frith, 2006; Buhle et al., 2014). In line with this evidence of similarities, we argue that virtual humans are capable of triggering neural responses attributable to the social domain. Apart from an emotional reaction to virtual humans, people also instinctively follow social and cognitive conventions such as mutual gaze with them (Bailenson, Blascovich, Beall, Loomis, & Bulletin, 2003; Bailenson, Blascovich, Beall, Loomis, & Environments, 2001). Although these non-verbal conventions may not fully account for day to day conversations between people, they are indeed capable of triggering neural responses in humans and evidences exist to back this up (Hari, Henriksson, Malinen, & Parkkonen, 2015; Schilbach et al., 2006). However, of all these studies, only Schilbach and colleagues (2006) has attempted to investigate the neural correlates of virtual human perception. Schilbach and colleagues' study (discussed in the literature review) investigated participants perception of being involved in a conversation when they are being gazed at by a virtual human avatar. This was compared to their perception when the avatar was gazing at another virtual human assumed to be within the scene, but not visible to the participant. The findings from this study showed the implication of the DLPFC when participants felt they were part of the conversation, compared to the other scenario. This study, like most previous studies lacking in neuroimaging component, only focused on non-verbal cues (eye-gazes in Schilbach and colleagues' studies). We define participants' involvement in interactions of this nature as passive.

Day to day conversation comprises of verbal and non-verbal conversation. Following this, we argue that the focus on passive interaction does not adequately represent social interaction. Meanwhile, an experiment focusing on passive interaction does not show mundane realism as highlighted by Allport's (1985) experimental control – mundane realism trade-off described in section 2.3.1. This shortcoming is further strengthened by the argument that different neural correlates exist for speech production and muteness (Dronkers & Ogar, 2004). Also, Schilbach and colleagues (2006) adopted the fMRI which is characterised by restrictions to the naturalistic movement of participants. The fMRI also restricts natural non-verbal communication. An alternative approach to restricted movement will involve neuro-imaging capture after the experiment has been completed. We argue that this tool may not be ideal for measuring social interaction, therefore our study uses the fNIRS. The fNIRS allows for a more naturalistic data capture which suits the current research. Meanwhile, virtual humans also bring the advantage of repeatability as real humans can be affected by several factors, hence the choice of virtual humans for this research.

In summary, we understand that virtual humans are capable of triggering responses similar to real humans if they meet the behavioural realism criteria (Blascovich et al., 2002); however, we believe that the neural correlates of these responses will provide more formidable evidence. We also understand neuroimaging tools exist to measure the neural basis of cognitive activity naturalistically. Moreover, studies on exposure therapy suggest similarities between the outcome of VR based therapy and in vivo therapies (Freeman et al., 2017); and neural correlates of social interaction during "passive" interaction where the participants only employ non-verbal cues have also been explored. However, no study has attempted to investigate the neural correlates of social interaction from a day to day like activity where participants employ both verbal and non-verbal cues (active conversation). Following these, we attempt to investigate if virtual humans are indeed capable of triggering measurable neural response during "active" conversation with humans. If they are, is this response indicative of inhibition? And what display is suitable for effective implementation of this system?

3.4 Research Question

Literature review shows that virtual humans have been extensively adopted in studies of emotion and perception (mainly from the computer science perspective). They have also featured widely in human-computer interaction (HCI) studies and are arguably part of HCI (Cassell, 2000; Kenny, 2007). However, only a few studies were found that have explored the neural basis of interaction with virtual humans. Of these studies, Schilbach (2006) is closest to our research. Schilbach (2006) performed an fMRI study to investigate the neural correlates of being personally involved in social interaction as opposed to being a passive observer of social interaction between others. However, this study explores only non-verbal communication (gaze) which can easily be fitted into conventional neuro-imaging blocks. At the time of the initial literature review and throughout the PhD, we were unable to find any study that investigated the neural correlates of a more naturalistic conversation with virtual characters.

This may be consequent to the difficulty in tying naturalistic conversations to structured blocks. And complexities with analysing the data.

This research, therefore, seeks to answer these questions:

Are virtual humans capable of triggering measurable prefrontal cortex (PFC) responses in real humans during social interaction?

Is this neural response indicative of inhibition?

This research targeted VR head-mounted displays (HMDs) because of its portability, this changed slightly through the PhD journey and different display systems were adopted in each of the three studies. An extra research question emerged from this story:

What kind of display system is best suited to study this?

3.5 Approach

After literature review, the experimental design was considered. The initial aim (at the start of the research) of the experiment was to investigate if virtual humans are capable of triggering measurable neural (PFC) responses indicative of inhibition during conversations with participants using an immersive virtual reality head-mounted display (HMD), the oculus rift and a neuro-imaging tool, the fNIRS.

We learnt from VR related works of literature that immersion enhances perception, hence our choice of an HMD. We also learnt from previous studies that the PFC is implicated during executive functioning (one of which is inhibition); following this learning, we argue that a neuro-imaging tool capable of investigating PFC response can also present neural responses indicative of inhibition in humans, or show indicators to these responses.

It is not unusual to have simulator sickness measured in virtual environments and virtual reality studies (Kennedy et al., 1993). This sickness is however mostly associated with delays in viewpoint update compared to head movement and limited fields of view in simulations. This is usually exaggerated in simulations involving the motion of virtual objects in virtual environments. The simulations developed for our studies did not involve the movement of objects in virtual space. Moreover, the simulations were such that participants were seated throughout the experiments looking straight at the virtual human confederate positioned directly in front of them.

The first experiment shared the aim of the general PhD and sought to answer the research questions using an HMD. This experiment was carried out after Ethical approval had been obtained from the University of Salford, Research, Innovation and Academic Engagement Ethical Approval Panel with approval number -HSR1617-90. Mobility of the system was a key consideration at the time when this experiment was designed hence the choice of the Oculus rift DK2. A pilot consisting of N=5 participants was carried out to ascertain the feasibility and get feedback from participants. After the pilot, N=20 participants took part in the within-subject experiment which investigated the neural basis of social interaction with live-sized virtual humans in an immersive head-mounted virtual reality display. The independent variable for this experiment was friendliness/unfriendliness of virtual human confederate. The dependent variables were dorsolateral prefrontal cortex (DLPFC), medial prefrontal cortex (MPFC) activation and likeability of virtual human confederates which was captured using the likeability section of a standard Godspeed questionnaire series. Findings show that prior experience with VR and gaming affected activation within our regions of interest, however, for participants with little or no prior experience with VR and gaming, increased activation was identified in the DLPFC during the conversation with the unfriendly (confrontational) virtual human confederate. Meanwhile, we encountered a high data exclusion rate during initial data analysis (N=10 participants were excluded). This high data exclusion rate was attributed to the cumbersomeness of the equipment (the HMD and neuro-imaging cap). This suggested a need for a second study.

The second study aimed to investigate the outcome of the experimental setup with reduced cumbersomeness and compare the outcome with that of the initial analysis of the first study. This study was similar to the first study, the only difference being that a large display screen was used in this study in place of the HMD used in the first and for this, ethical approval was also obtained. The number of participants was informed by the number of valid results from the first study (N = 10). Data exclusion was low in this study. Yet the outcome (using the region of interest analysis) failed to show a statistically significant difference with the outcome of the first study. However, feedback from reviewers on a publication submitted by Aleksandra Landowska (within the group) suggested that the lower band-pass filters being adopted in our data analysis were wrong. This led to a further analysis of the outcomes of both studies. Before this feedback, the low band-pass filter used within the group for our experiments was the default low band-pass filters set by NIRSLab which was a value of “0.01”. NIRSLab is the software for analysing fNIRS data. The default value set assumed that a block design had been adopted and that each experimental block lasted for 100 seconds. The low band-pass value is usually the reciprocal of the time spent on each experimental block. Since the time varied for each condition and participant, a significant amount of our data was considered to be noise when analysed using the default value set by NIRSLab. Further analysis after considering and implementing feedback from reviewers showed an increased number of valid data in the first study; changes were not made to the second study as data gathering had been completed and analysis was ongoing. The outcomes using both filters are reported in dedicated chapters for each of the studies. Meanwhile, the outcome of this experiment using the low band-pass filters failed to show any statistically significant increase in activation during the conversation with the unfriendly virtual human confederate, instead, a statistically significant decrease was shown across the group of participants regardless of prior level of experience with VR and gaming.

The third study sits in between the first two studies. The aim cuts across the individual aims of the first two studies. The aim was to determine if virtual humans are capable of triggering measurable neural responses indicative of inhibition during conversations with participants in a non-cumbersome immersive display system. The need for the third study was identified by the previous examiners. The examiners argued that the difference in perception of virtual humans could have been influenced by the difference in virtual human confederates used in each of the conditions for the first and second studies. They also argued that the non-counter balancing of conditions across participants did not show enough rigour. The third study remained largely similar to the previous two studies but incorporated the rigour highlighted by the examiners. The quality of the virtual human confederate was also improved upon with more realistic rendering and gestures. No new ethical approval was obtained for this study. This study was carried out in an immersive suite at Mary Seacole Building, University of Salford. N = 14 participants took place in this within-subject study. The dependent and independent variables of this experiment were the same as the first two studies. The outcome of this study showed a significant increase in DLPFC activity during the conversation with the unfriendly (confrontational) virtual human. This finding was consistent with the findings of our first study as well as several works of literature. The findings are further discussed in a subsequent chapter dedicated to this study.

While the studies varied slightly especially in mediums and goals, most components of these studies remained the same. These components are briefly discussed subsequently, and we attempt to highlight differences where they exist.

Meanwhile, the Hayling sentence completion task featured in the first two experiments. Our literature review shows that the Hayling task is one of the standard tests of executive functions which focuses on verbal initiation and suppression (Nathaniel-James, Fletcher, & Frith, 1997). The Hayling task described in section 2.7.2 also finds useful application in clinical studies targeting frontal lobe lesions (Bielak, Mansueti, Strauss, & Dixon, 2006; Pérez-Pérez et al., 2016). Being a recognised paradigm for assessing executive functions, with focus on inhibition, the Hayling task was introduced as a form of scale for comparing the outcome of the experimental task. We were interested in indicators that may have suggested similar patterns with inhibition as measured using the Hayling task. The Hayling task was chosen over other paradigms such as Stroop task and Simon test because of its relative ease of implementation and direct link with inhibition.

3.6 Measurement

The measurement remained the same across the three studies. The measures include haemodynamic changes within the DLPFC, haemodynamic changes within the MPFC, subjective impression of likeability as captured by the likeability section of the Godspeed questionnaire set.

Readings from the Hayling sentence completion task were only taken in the first two studies.

3.7 Technology and Tools

To evoke a response to simulated social stimuli we adopted:

Virtual Reality Head-mounted display (HMD):
For our first study, we investigated two HMDs – Oculus Rift and HTC VIVE. Although the Oculus was not designed to be worn with wearables such as a brain imaging cap, it presented higher feasibility for adaptation with wearable devices; this is owing to the nature of the plastic with which the Oculus was designed. The VIVE allows movement and thus natural interpersonal distance to be controlled by the participant. This study was however not particularly focused on interpersonal distance. Besides, given the means available to us, the feasibility for adaptation of the VIVE with wearable devices was low. After initial piloting, we settled for the Oculus Rift. The process for the adaptation of the oculus rift has been described earlier. Figure 2 shows the oculus rift DK2 adapted for our purpose.

Figure 2 modified oculus rift DK2 adapted for this research

Large Screen Display:

For the second study, we settled for a Samsung 50-inch display screen (Figure 3). This was partly due to availability and the fact that this device sufficiently serves the purpose of this study.

Figure 3 Display screen adopted for this research

Immersive Screen/Display:

For the third study, we used surround projection. However, we had the options of using a viewpoint tracked stereo in a CAVE-like environment, or static viewpoint projection onto the walls and floor of a clinic-like space. We chose the latter, as it was a technology that could be readily deployed to a clinic, did not require any glasses or tracking paraphernalia to be worn and was comparatively inexpensive. Since the experiment required users to be sat in a place and looking primarily in one direction, we did not have a strong need for tracking viewpoint provided screens surrounded the normal field of view. As the agent and user had a table between them, they were not close enough for stereo to have a large impact. It is possible that not tracking viewpoint or providing stereo might reduce the feeling of presence, however, so might wearing equipment on the head. Experience built up over years of experiments by our group, suggests that, because of this compromise, stereo and viewpoint tracking should be used only when there is a compelling reason to do so

Figure 4 Immersive suite with a projection of our VR simulation

Meanwhile, to obtain the measurements listed above we adopted:

Brain Imaging Technology:

This was used to evaluate PFC response to social (and possibly anti-social) stimuli in our participants during the experiments (Figure 5). Since we were primarily concerned with the frontal Lobe (consequent to the available technology), we adopted the NIRxNIRSport which is a non-invasive, portable brain imaging system consisting of 8 sources and 8 detectors; as well as the fNIRS which measures the absorption of the near-infrared light between 650 and 950 nm through the intact skull.

Figure 5 NIRxNIRSport

Questionnaires:

Several attempts have been made to develop standardized questionnaires for measuring human impressions of Robots (Bartneck, Croft, & Kulic, 2008; Bartneck, Kulić, Croft, & Zoghbi, 2009; Haring, Matsumoto, & Watanabe, 2013), but the Godspeed questionnaire featured most; therefore, we adopt this questionnaire. The Godspeed questionnaire is divided into five sections: anthropomorphism, animacy, likeability, perceived intelligence and safety. Each section measures parameters on a 5-point Likert scale.

The anthropomorphism section measures the following parameters: fake/natural, machinelike/humanlike, unconscious/conscious, artificial/lifelike and moving rigidly/moving elegantly.

The animacy section measures dead/alive, stagnant/lively, mechanical/organic, artificial/lifelike, inert/interactive and apathetic/responsive.

The likeability section measures like/dislike, unfriendly/friendly, unkind/kind, unpleasant/pleasant and awful/nice.

The perceived intelligence section measures incompetent/competent, ignorant/knowledgeable, irresponsible/responsible, unintelligent/intelligent and foolish/sensible.

The perceived safety section measures anxious/relaxed, agitated/calm and quiescent/surprised. In total, this questionnaire contains 24 questions which are mentioned on a 5-point Likert scale as mentioned earlier.

Whilst the results from sections on anthropomorphism and animacy were used in evaluating the quality of the virtual human confederates, sections on likeability, perceived intelligence and perceived safety were our primary focus. Godspeed questionnaire originally targets human perception of robots (Bartneck, Kulić), however, it has also featured in studies measuring perception of virtual confederates (Bartneck, Kulić, Croft, & Zoghbi, 2009); it, therefore, suits our study. A copy of the actual questionnaire is also attached to the appendix.

To validate and or exclude data:

Signal Quality, Signal to Noise Ratio (SNR) and interference was measured with NIRsLab. This measures quality of fNIRS data capture. This is controlled from within a software called nirsLAB. nirsLAB is a free software for analysing fNIRS data.
Godspeed questionnaire: Sections on Anthropomorphism, perceived intelligence and animacy test if the virtual humans are of sufficient quality.

3.8 Participants

Study 1
N = 20 participants undertook a within-study design experiment.
We targeted volunteers within and outside the University. Emails were sent to participants through the departmental offices as well as advertisements on social media. We targeted volunteers within Manchester as we wanted to keep reimbursements as minimal as possible. There were no specific interests in ethnicity, demographics or cultural orientation of our subjects. However, we ensured participants were above the age of 18.

Study 2
N = 10 participants undertook a within-study design experiment.
Recruitment was similar to that of Study 1.

Study 3
N = 14 participants undertook a within-study design experiment.
Recruitment was similar to the previous two studies.

3.9 Procedure

Although the procedure was similar in all three studies, some aspects of the procedure were peculiar to each study. Here we attempt to highlight those procedures that cut across each of the studies. Peculiar procedures such as the administration of the Hayling task are discussed in chapters dedicated to each study.

There was a familiarization period for the virtual condition. During this period, the participants explored the VR environment to attempt to eliminate any excitement arising from the simulation. Familiarization period was provided for in all three studies. During the familiarization period, our participants were not required to wear the fNIRS as we were not interested in measuring the neural activity at this stage. Meanwhile, we understand that neuroimaging tools are not particularly comfortable (especially concerning the first study); as a result, we attempted to keep the length of time for which the fNIRS was worn by our participants at a minimal.

There was also a *baseline* where the participants were advised to attempt to do nothing.

Each condition of the experiment lasted for approximately three (3) minutes.

In line with ethical and health/safety procedures, participants were provided with a consent form and participant information sheet. Each participant was allowed ten (10) to fifteen (15) minutes to complete this form.

Once ethics and health/safety procedures were completed, participants were prepared for the familiarization stage. At the end of the familiarization stage, the fNIRS was then put on the participant for baseline and actual data capture.

3.10 Task

For the first two experiments, a standard Hayling sentence completion task was first administered. This consisted of fifteen partly completed sentences, similar to the standard Hayling task (Appendix 11). The rationale for the inclusion of the Hayling task is provided at the end of section 3.5. All the participants for these experiments underwent the Hayling sentence completion task. The task consists of two conditions; in the first condition, participants were asked to complete a partly completed sentence with a word or phrase that makes sense. In the second condition, the participants were asked to complete the sentence with a word or phrase that does not make sense. The Hayling task was administered in a within-subject design and the order of the conditions was the same for all participants. For the first experiment, the latency of response to each of the sentences was recorded using a stopwatch which was started immediately the question was asked and stopped once an answer was given. A recording was also made using a voice recorder so that the process could be revisited, and time measurements validated when necessary. For the second experiment, readings were captured using the fNIRS. Apart from the differences in measurement, every other thing remained the same as the first experiment. The analysis of the Hayling task is captured in Section 3.11. The experimental task followed the administration of the Hayling task.

Each participant was asked to hold a conversation with a virtual human about topics of current affairs (as specified earlier). They were given no other instructions or goals other than to suppress any anti-social or socially antagonistic behaviour during the experiment (in some cases) and directives on how to stop the experiment if they wish. Details of the tasks including decisions are presented in individual experiment chapters.

The first virtual confederate attempted to hold a friendly conversation with the participant. After neural sampling, a second confederate attempted to hold the same conversation in aggression. This "aggressive" virtual human used moderately confrontational verbal and non-verbal communication likely to trigger a moderate emotional response in our participants. These cues include longer gazes, sitting upright and tapping of feet; intermittent breaking of participants' sentences by the virtual human was also adopted (Matsumoto, 2006). The decisions behind our choices depend largely on implementable features and available technology; this is discussed in Section 3.15. The order of the conditions was counter-balanced in the third study.

At the end of the experiment, participants were asked to fill a questionnaire aimed at capturing their perception of the confederates. The participants were also interviewed informally to capture possible findings not targeted by the questionnaire.

3.11 Data Analysis

We have adopted quantitative methods in our data collection. However, we obtained consent from participants to video record them during the experiment to monitor gestures, behavioural responses and interesting sequences of conversation.

3.11.1 Quantitative Data Analysis

Functional brain imaging data were analysed using NIRSLab Software (which uses statistical parametric mapping and general linear model analysis). We utilized statistical parametric mapping (SPM) approach to compute hemodynamic responses of the brain.

Questionnaire data were analysed using SPSS. Changes in perception of behaviour and opinions of the virtual humans were calculated using the paired sample T-test.

Signal Quality, Signal to Noise Ratio (SNR) and interference was analysed using NIRStar (this information was required to show the validity of the data captured by the fNIRS).

Hayling task data were analysed in the first experiment by comparing the time taken to complete the sentences with words or phrases that make sense and the time taken to complete the sentences with words or phrases that do not make sense, a correlation was then carried out between the outcome of the Hayling task and the main experimental task. However, we acknowledge that the sample size was not enough for a correlation.

In the second experiment, the fNIRS was worn during the Hayling task. The data was then analysed using the NIRSLab, similarly to the experimental task.

SYSTEM DESIGN METHODOLOGY

3.12 Background

Interactions between humans thrive when there is a perception of friendliness from some or all the interacting parties (Simon, 1952). This perception is often dependent on verbal and non-verbal gestures displayed by the individuals in question (Moskowitz, 1993). A perception of unfriendliness often hinders interaction (Simon, 1952).

We explore gestures indicative of unfriendliness, on one hand, creating virtual humans on the other hand, and implementing these gestures on the created virtual humans. We believe that the absence of unfriendly gestures in the implementation makes a virtual human confederate either friendly or neutral depending on other gestures present; therefore, we focus more on those unfriendly gestures during the design.

3.13 Aggression

Whilst several behaviours can be referred to as unfriendly, a common one is aggression (Hammock, Richardson, Williams, & Janit, 2015). Aggression is generally defined as behaviour that tends to cause physical harm and personal injury (Bandura, 1978). Personal injury here refers to bodily and emotional harm.

Aggressive and anti-social behaviour have been explored severally across disciplines. Some studies have looked at these from the gender point of view (Eme, 2016; Pepler, Madsen, Webster, & Levene, 2014; Shaban & Kumar, 2016) while several others have considered them along the lines of cultural backgrounds (Fry & Gabriel, 1994). Eme (2016) suggested that aggression has mostly been considered from the biological and environmental viewpoint in which case, attaching aggression to the male gender is common. Biological viewpoint refers to the physical structure while the environmental viewpoint refers to a normative acceptance within a group of people. Eme (2016) however suggested that the distinction between aggression in the male and female gender can be accounted for in terms of evolution and he attempted to explain this from the perspective of evolutionary developmental psychopathology (EDP). Fry and Gabriel (1994) acknowledged the distinction in aggression between gender; however, they suggested that some cultures tend to valorise aggression in males and pathologize identical behaviour by females, and consequent to this, these behaviours tend to be less exhibited by females. Pepler and colleagues (2014) also highlighted the lack of attention in research to aggressive behaviour by young females. Although this research had no interest in gender bias, it may be an interesting consideration in the future.

Bandura (1978) argues that the extent to which people perceive aggressiveness varies across individuals. That is, the higher the aggressive personality traits possessed by a person, the higher the person’s chances of getting aggressive at any given point in time (Infante & Wigley III, 1986).

During a conversation between two or more individuals, the type of aggression that features is referred to as verbal aggression (Infante & Wigley III, 1986). Infante and Wigley (1986) having widely explored verbal aggression, conceptualizes it as a personality trait that predisposes one to attack the self-concepts of other instead of, or in addition to their positions on the topic of conversation. The arguments from Infante and Wigley (1986) still form the basis of several studies today.

Closely related to verbal aggressiveness is argument (Hample & Anagondahalli, 2015; Infante & Wigley III, 1986). Verbal aggressiveness differs slightly from argument in that during arguments, only the positions of opposing parties on the subject are targeted (Hample & Anagondahalli, 2015). unlike in verbal aggression where self-concepts are verbally attacked alongside position (Aloia & Solomon, 2016).

Whilst verbal social aggression appears to be similar across individuals, non-verbal social aggression varies across gender (Underwood, 2004) and culture (Matsumoto, 2006). Matsumoto (2006) argued that non-verbal behaviours such as gaze vary across contact cultures and their non-contact counterparts. The term contact cultures, in this case, refers to cultures that facilitate physical touch or contact. Individuals from contact cultures will primarily gaze much longer and directly during friendly social interaction than those from non-contact cultures (Matsumoto, 2006). Moreover, shorter interpersonal distances are also observed by individuals from contact cultures (Matsumoto, 2006). Efron (1941) argue that distinct gestures are shown by people of different cultures; however, these distinctions tend to disappear when they are assimilated into larger societies. Several other studies have argued in line with Efron (1941) (Martínez, 2016; B. Miller, 2017).

3.14 Perception of Virtual Humans

Like humans, perception of non-humans has also been widely studied in Human Robotics Interaction (HRI) (Weiss, 2015). Studies are increasingly showing that virtual reality components are perceived the same way as real-life components (Hoffman et al., 2004). Our literature review of virtual humans (section 2.3.1) suggest that virtual humans are capable of triggering desired social responses in humans (de Borst & de Gelder, 2015), this justifies the adoption of virtual human confederates throughout this study. Moreover, the possibility of repeating experimental conditions pitches virtual confederates over their real human counterparts.

This section primarily describes the methods adopted in our system design and implementation; however, we also explore the perception of the virtual confederates and attempt to quantify and validate this perception using a standardized questionnaire. We have adopted the Godspeed questionnaire for this study. Several attempts have been made to develop standardized questionnaires for measuring human impressions of Robots (Bartneck, Croft, & Kulic, 2008; Bartneck, Kulić, Croft, & Zoghbi, 2009; Haring, Matsumoto, & Watanabe, 2013), but the Godspeed questionnaire featured most; therefore, we adopt this questionnaire.

Our study builds on past studies in this area and attempts to produce a system of virtual humans that exhibit the primary verbal and non-verbal gestures identified in the literature.

Two virtual human confederates are produced: a friendly (verbally non-aggressive), and an unfriendly (verbally aggressive) virtual confederate. We aim to establish the difference in participants’ perception of these two virtual humans as measured by the likeability section of the Godspeed Questionnaire. The system is tested in an experiment aimed at triggering emotional responses in participants during a conversation task and participants’ perception of our virtual humans are measured and reported.

3.15 System Design, Development and Implementation

For this study, we have adopted the spiral software development life cycle (SDLC) methodology. The spiral methodology is suitable for designs where the outcome of a system is not certain (Boehm, 1989). It also incorporates other SDLC models and allows for concurrency in requirement gathering and design. We briefly outline the stages of the spiral methodology in relation to our implementation.

3.15.1 Phase1: Objectives Determination

Requirements gathering, planning and feasibility studies were initially carried out. No different objectives were specified apart from the objectives of the study. Some key considerations at this phase include available technology, technology adoption and justification, cost-effectiveness, scalability and deliverables. The functional and non-functional requirements were clearly defined, and likely constraints identified at this stage.

Functional Requirements

- The system shall have at least 2 virtual humans
- First virtual human shall attempt to hold a friendly conversation
- Second virtual human shall attempt to hold a confrontational conversation
- Virtual human animations, which include all gestures and playback of recorded audio shall be controlled by keypress events from a personal computer (PC) keypad.

Non-Functional Requirements

- The system shall be run on a virtual reality head-mounted display
- Virtual humans shall display verbal and non-verbal cues

The choice of friendly and unfriendly attributes for the virtual human confederate is based on measurements from the likeability section of the standard Godspeed questionnaire. Behaviours that suggest antisocial behaviour and aggression were studied and incorporated into the design of virtual humans. Aggression is a common form of unfriendly behaviour (Hammock, Richardson, Williams, & Janit, 2015), and has multiple implementations commercially in game engines and 3D modelling platforms. However, although this implementation was sufficient to differentiate between friendly and unfriendly virtual human confederates, it is arguably subjective and maybe better targeted in future studies.

The commercially available adobe mixamo animations were adopted in the final implementation of the virtual human confederates. The adopted animations for the unfriendly virtual human confederate include “sitting angry”, “angry gesture”, “angry point”, “angry”, “idle”, “sad idle”, “sarcastic head nod”, and “sitting disbelief”. These animations were slightly modified to work with humanoid objects on Unity3D. Furthermore, tapping of feet and intermittent interruption of participants’ responses earlier mentioned in section 3.10 were also adopted for the unfriendly virtual human confederate. The tapping of feet was implemented through motion capture with the Microsoft Kinect, while the intermittent interruption was implemented using Microsoft Visual Studio C# keypress events. For the friendly virtual human confederate, the adopted mixamo animations include “idle”, “sitting idle”, “happy idle”, “happy”, “happy hand gesture”, “head nod yes” and “thoughtful head nod”. These animations were blended using the animation blend/transition tool of Unity3D. Meanwhile, the facial expressions implemented in Lipsync pro for Unity3D was attached to the confederates. We adopted the gestures for happy (for the friendly virtual human confederate) and unhappy (for the unfriendly virtual human confederate) which were already implemented in Lipsync pro. Eye movement for the confederates was implemented using the EyeController that ships with Lipsync pro. Similar to the facial expressions, we adopted the eye movement for happy (for the friendly virtual human confederate) and unhappy (for the unfriendly virtual human confederate) which ware already implemented in EyeController.

The verbal conversation was enhanced by non-verbal cues such as tone, rate volume and the body languages (captured by the animations above). The sets of sentences were presented to our volunteers and the voice recordings were made independently. One of the volunteers was asked to play the role of a friendly confederate while the other was asked to play the role of the unfriendly virtual human confederate. As a result of this independent recordings, there are some discrepancies with words used by each of the confederates. The volunteers were also asked to use non-verbal cues that are useful to their roles. For instance, the volunteer for the friendly confederate recorded with a friendly tone, a moderate volume and to talk at a moderate rate; while the volunteer for the non-friendly confederate recorded with an unfriendly tone, a high speech volume and talked at a faster rate (Kiani, Balouchi, & Shahsavani, 2016; Spieler & Miltenberger, 2017). These recordings happened more than once and the best were selected and lipsynced with the virtual human confederates. Although the outcome using this approach showed significant differences between the perception of the virtual human confederates as measured by the likeability section of the Godspeed questionnaire, we acknowledge that this setup will benefit from a more principled approach in the future, and perhaps the use of trained actors. The full conversation script is attached to Appendix 10.

3.15.2 Phase 2: Identification and Resolution of Risks

The system is unlikely to trigger hazardous risk. We, therefore, considered risk in terms of timelines, quality of expected deliverables, alternative technologies and skills/experience within the research team. The key considerations in Phase 1 were carried out in more details; possible constraints within these considerations were also factored. Some considerations in this phase include:

- CAVE / HMD Technology
- HTC Vive / Oculus Rift
- Unity 3D / Unreal
- C# / JavaScript
- Build from scratch / Reuse already existing systems
- Budget for paid packages
- Natural Language Processing / Wizard of Oz approach

While Phase1 considered feasibility on a general scale, this phase considered feasibility within the time frame and available resources with respect to this study.

3.15.3 Phase 3: Development and Test

This phase involved a detailed design, implementation and critical testing of the deliverables. Unlike most software product designs; the design of the virtual humans was not fitted into a flowchart. We identified tools that are efficient in creating virtual characters/avatars and added animations (verbal and non-verbal cues) to these characters. Non-verbal cues were investigated during literature review (Section 2.4.2) and we attempted to implement these cues with the available options.

The tools adopted in implementing our system are described briefly:

SOFTWARE

The VR system was implemented using the free Unity 3D personal edition. Unity 3D is a 3D engine for creating 3D games and applications for mobile, desktop, the web and consoles.

Our early virtual human prototypes were created using DAZ studio. DAZ Studio is a free 3D morphing, posing and rendering suite. It ships with standard genesis 3D characters that can be rendered exported in fbx formats that are useable in Unity3D

We specifically used the DUF facial animation package for DAZ studio that ships with iClone pro. This package worked within DAZ studio and was also useful in creating our later stage virtual human prototypes. iClone is a paid tool for creating realistic looking animation ready 3D characters for use within the Reallusion family of products. We picked up some in-built animations from this tool and did some realtime motion capture using the Microsoft Kinect within the iClone package. 3DXchange pipeline (also part of the Reallusion family of products) was instrumental in converting these animations and motion captures to other formats, especially fbx for Unity 3D.

Adobe fuse is a tool for creating customizable 3D characters. This package is part of the Adobe Creative Cloud collections and is not available for free. The Mixamo store has free ready to use mixamo characters and animations in formats usable in Unity 3D. 3D characters created in Adobe fuse can be uploaded to the mixamo store and used as a mixamo character. We have adopted mixamo characters as the final prototype of our first two studies and customised Adobe fuse characters for our third study. In all experiments, we have used a combination of mixamo animations generated from motion capture using the Microsoft Kinect.

All Lipsync and eye movement (gaze) controlling within our system have been created using this package. LipSync is a tool for creating expressive speech; it ships with customizable phonemes, emotions and mouth movements. This product works seamlessly within Unity 3D; however, it is not available for free. EyeController is part of the LipSync pro package which controls eye movement during conversations. We have simulated our eye gaze movement using EyeController. These features are essential for the quality of the virtual human confederates. This is particularly useful for the anthropomorphism and animacy sections of Godspeed questionnaire.

HARDWARE

We used the Microsoft Kinect for motion capture of non-verbal cues that are likely to be seen during a conversation. This capture was initially done as a standalone, fine-tuned and exported to DAZ Studio and Unity eventually. Subsequent usage was within iClone later in our design.

High graphic PC (Preferably NVIDIA GTX-Powered PC) was adopted throughout the design and implementation of the VR system. This was useful because the software packages required high powered graphic card PCs.

DECISIONS

Apart from the planning of hardware and software design, key decisions were made from learning outcomes of initial and subsequent piloting.

The first virtual humans designed were DAZ 3D studio virtual characters. These characters had inbuilt non-verbal gestures which were timed and exported with the characters into fbx format. Although these characters met the primary requirement of being exportable to Unity3D and Unreal engine (which are the two most popular 3D game design software), the characters the gestures were only limited to the options in the animation list in Daz 3D studio. Another problem with these virtual characters was the fact that some of the animations were not compatible with the humanoid form on Unity3D, therefore the characters were largely unrealistic. Feedback from examiners within the first year of the PhD also suggested this.

IMPLEMENTATION

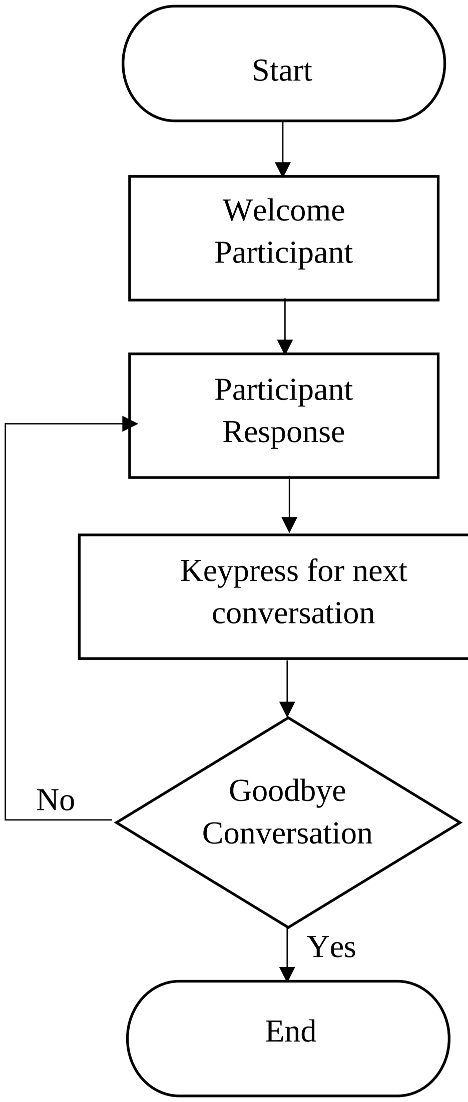


Figure 6 Flowchart of System design

Figure 6 represents the flowchart for the two confederates detailed in our methodology. While the first confederate attempts to welcome participants and end conversations nicely, the second confederate attempts to do this aggressively. Table 2 shows the actual “Welcome Participant” and “Goodbye Conversation” processes in Figure 6 for each confederate.

	Welcome Participant	Goodbye Conversation
Confederate 1	Hi, my name is Chris, it’s nice having you here, how are you?	I’ve enjoyed talking to you.
Confederate 2	You were supposed to be here a while ago, it’s really rude to be late and not even apologise. I suppose we just carry on with this conversation and see if we’ll get some useful data off this conversation.	That’s enough. I’ve got to go.

Table 2 *Contrast between conversational patterns of the two virtual human confederates*

The Wizard of Oz approach was adopted and implemented using C# as well as the tools listed above. Animation transitions were tied to key presses. The Wizard of Oz approach entails controlling the virtual human confederates through button presses and it has been adopted by several studies in the past (Shiomi, Kanda, Koizumi, Ishiguro, & Hagita, 2007; Weiss et al., 2009). Using WOz removes quality of machine intelligence from impacting on interactions and thus results. WOz is a simple form of semi-automated animation (Manning, 2014; Liddy, 2001). Rigged animations were saved to files as well as audio recordings of the virtual human conversation. These were then controlled through button presses; for instance, pressing the key “1” on the keypad makes the friendly virtual human confederate sit relaxed and welcomes participant. The key “0” makes the virtual human confederate terminate the conversation. Some gestures such as adjusting sitting position and looking sideways occasionally were randomised. However, gestures tied to the button presses take priority.

The prototype was tested within the group; feedbacks were taken into consideration for subsequent specification.

3.15.4 Phase 4: Plan next Iteration

The outcome of phase 3 was demonstrated within the group; the feedback was considered and the process was re-iterated. The iteration happened three times; prototypes were produced for each iteration and improved upon in the next iteration.

Prototypes

An initial prototype of virtual humans for this study was produced while requirements gathering was on-going. This early prototype was aimed at investigating feasibility early enough in the design. We describe our prototypes and their features below. The software tools adopted in the creation of these prototypes are also specified as different tools had been utilised within different iterations.

Prototype 1

A DAZ Studio Genesis 3D male virtual character (Figure 7). This was an early prototype and was lacking in a good number of expectations. However, it was good enough to investigate feasibility and feedback from independent observers.

Features:

- pre-recorded animations (using Microsoft Kinect).
- Exportable to Unity 3D usable format.

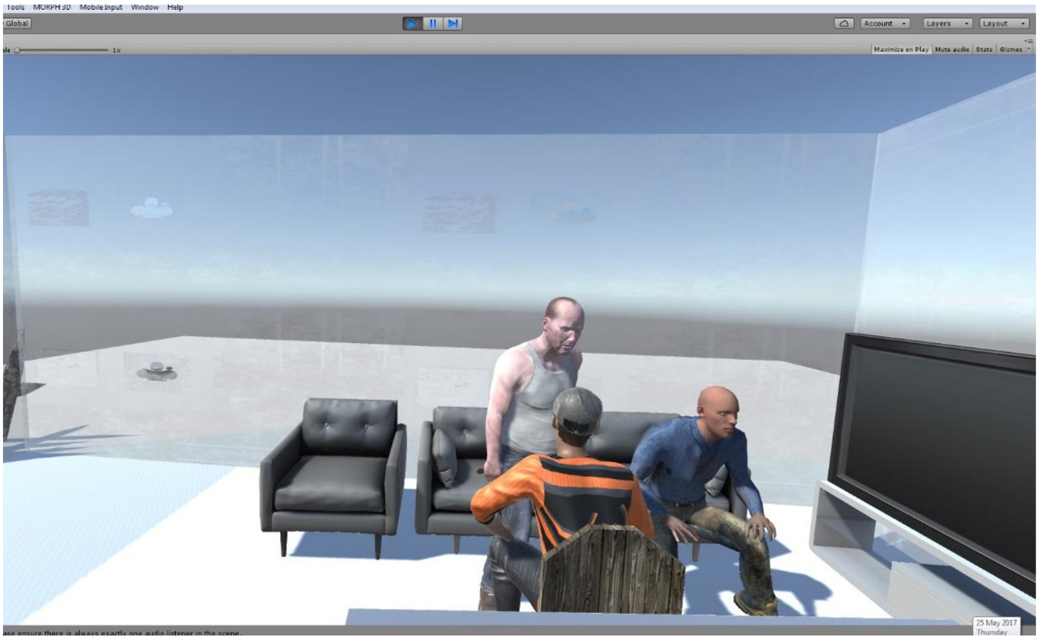
Figure 7 Early prototype of virtual human

Prototype 2

An extended version of Prototype 1. This character was successfully exported into a Unity 3D scene and could interact with other assets within Unity3D. This prototype was an attempt at creating virtual humans that could move their mouths to simulate conversations. While lip syncing appeared feasible at this stage (from the implementation of mouth movement), it seemed farfetched. Multiple instances of this prototype were created, and their animation components re-used across characters (Figure 8).

Features:

- mouth movement, facial expressions/animations, eyebrow movement and blinking (implemented with the iClone 6 Facekey for Genesis characters).
- improved animations with better transitioning (implemented with templates from iClone 6 alongside pre-recorded animations in Prototype 1).
- reusable animation components with similar objects.
- audio recordings of conversations aimed at being played back in sync with the mouth movement.



ase ensure there is always exactly one audio listener in the scene.

Figure 8 Improved prototypes with mouth movement and facial animation imported into Unity3D

Prototype 3

Improved mixamo store virtual characters within a social setting in a Unity3D pub scene. We retained all features of prototype 2. The mouth movement of the virtual characters was in sync with the recorded audio in this prototype. This prototype also implements EyeController, which controls eye gaze movement (Figure 9).

Features:

- lip sync (implemented with LipSync Pro).
- improved facial animation/expression options.
- eye movement and gaze control.

- improved animation.

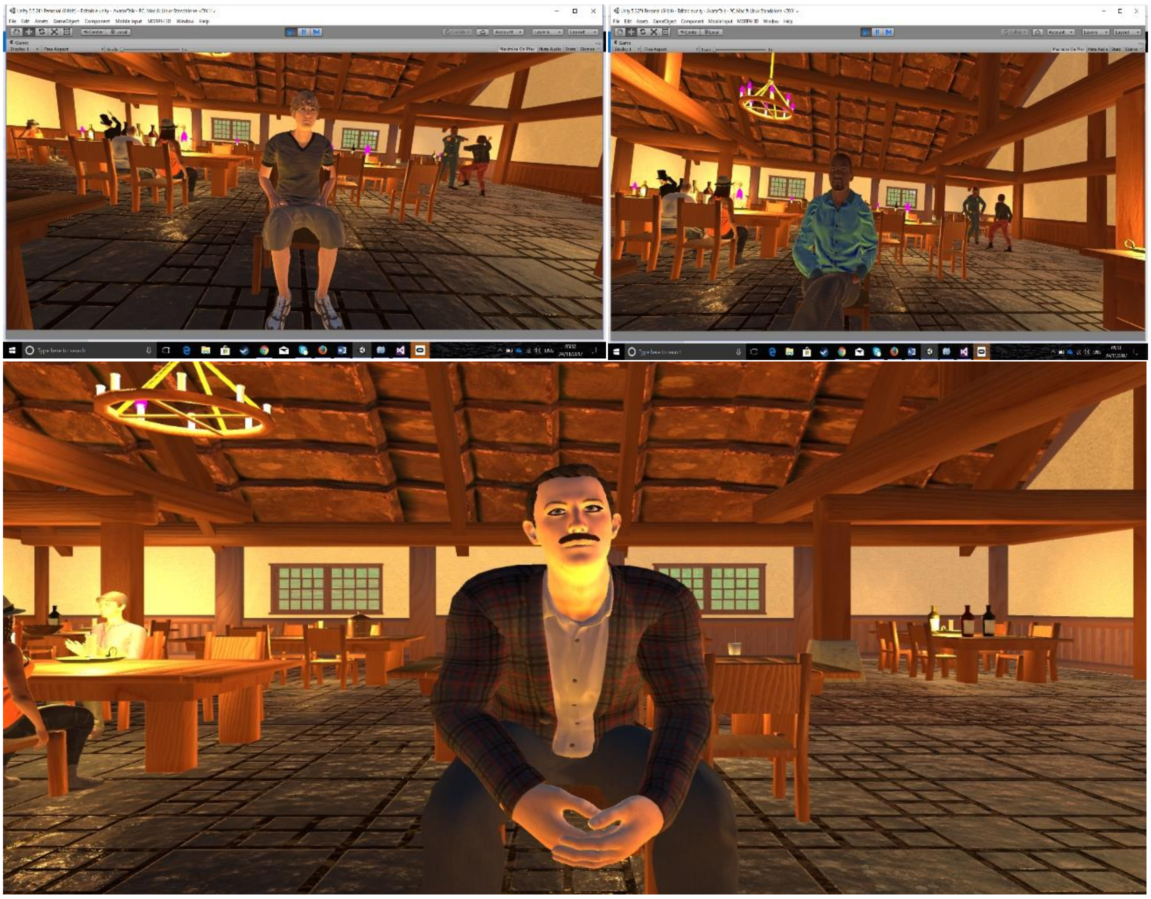


Figure 9 Enhanced virtual humans with lipsync and improved gestures

CHAPTER 4

STUDY 1 – HEAD MOUNTED DISPLAY

4.1 INTRODUCTION

In this chapter, we discuss our first study. This study follows series of evaluation of our virtual human prototypes as well as an initial pilot of the experiment within the group. In this study N=20 healthy participants were involved in social interaction with two different virtual humans, one being friendly and the other being antagonistic. The study was carried out using a combination of a virtual reality head-mounted display and the functional near infrared spectroscopy fNIRS. The scope and methods of this study are discussed in the chapter.

We report the outcome of this study in terms of the neural correlates (as measured by the tools adopted) and participants' perception of the virtual humans (as measured by the likeability section of the Godspeed questionnaire series.

4.2 Scope

The neural responses targeted in this study are haemodynamic changes within the Prefrontal Cortex (PFC). Findings are therefore limited to the PFC.

While the PFC is traditionally believed to be responsible for executive functioning (Yuan & Raz, 2014), several other studies suggest other cortical regions play a huge part in these cognitive processes (Adolphs, 2009; Carpenter, Just, & Reichle, 2000; Gallagher & Frith, 2003). However, this study adopts the NIRSport device which is only capable of investigating neural correlates as reported within parts of the brain close to the surface, hence the focus on the PFC. Several studies sufficiently show the validity of PFC data in reporting executive functions (Carpenter et al., 2000; Wagner, Maril, Bjork, & Schacter, 2001); this study builds on such evidence, and we argue that the PFC data investigated in this study sufficiently represents the subject being investigated

Meanwhile, the findings might only apply to participants with no diagnosis of cognitive impairments or mental deficits.

The Wizard of Oz (WoOz) approach is adopted in this study. This approach entails controlling the virtual human confederates through button presses. Whilst some non-verbal gestures can be controlled with button presses, attempting to control autonomous gestures such as eye movement and gaze patterns will result in less believable virtual humans (Kallmann & Marsella, 2005); this suggests the need for a semi-autonomous virtual human that combines the attributes of the WoOz approach and that of an autonomous agent. Semi-autonomous agents have been adopted by several studies in the past (Riedl, Stern, Dini, & Alderman, 2008; Theune, Faas, Nijholt, & Heylen, 2002; Tomlinson et al., 2002) and is suitable for studies that focus on evoking particular kinds of emotion in participants (Tomlinson et al., 2002). An alternative approach is a combination of Automatic Speech Recognition (ASR) and Natural Language Processing (NLP) where responses by the virtual confederates are controlled by decoding the natural language of our participants (Martin & Jurafsky, 2009; Weber, 2002). The NLP approach tends to get out of control especially in cases where speech recognition systems fail (Cambria & White, 2014). Meanwhile, both repeatability and believability are important in this study, and achieving either with NLP adds unnecessary challenge and risk.

The virtual humans have been designed to be semi-autonomous, combining autonomous cues with the WoOz approach.

4.3 Methodology

4.3.1 Overview

N=20 healthy participants took part in a within-subject design experiment, where they conversed on an emotive subject with a friendly virtual human on one hand, and an unfriendly virtual human on the other hand.

All experimental design and procedure have been carried out as approved by the University of Salford, Research, Innovation and Academic Engagement Ethical Approval Panel with approval number -HSR1617-90.

4.3.2 Task

Participants were immersed in a VR simulation of a public bar. They were then asked to hold a conversation with virtual confederates in turns. The conversation was centred on Brexit and the General elections (which were trending related topics at the time the experiments were carried out). The conversation was the same for both conditions. Participants were only instructed to suppress any resulting anti-social or socially antagonistic behaviour while they conversed with the virtual human confederates. An example of such behaviours is the use of improper language during conversations with the virtual human confederates, especially as a result of the actions of the virtual human confederate such as interrupting the participant. They were also given instructions on how to stop the experiment if they wished. The choice of Brexit and the General Elections was informed by the limitations of the neuro-imaging device. During initial piloting and testing, we encountered a problem with neuroimaging data analysis because the length of conversation was less than one minute for the first two pilot experiments. Following this, we chose an emotive topic to which participants will be interested to hold a conversation that may be long enough for neuro-imaging data capture. This was not without its problems also. One of the problems was that participants' emotional attachments to the topic varied, and since the fNIRS (and consequently the study) is only efficient in monitoring PFC activity, we cannot ascertain the extent to which the emotional attachment to the topic affected our outcome. The same concept was adopted in subsequent studies in the PhD.

4.3.3 Hypothesis

When a conversation with a friendly virtual confederate is taken over by an adversarial virtual counterpart,

Godspeed questionnaire data will show participants like the friendly virtual confederate better – H1.

Participants will exhibit an increase in activation of the dorsolateral prefrontal cortex (DLPFC) while conversing with the unfriendly virtual human confederate – H2.

Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) while conversing with the unfriendly virtual human confederate – H3.

4.3.4 Variables

The dependent variables for this study include likeability of virtual confederate (measured using the Godspeed questionnaire), DLPFC activation and MPFC activation.

Meanwhile, the independent variable is the friendliness of virtual human confederate. We shall define the experimental condition as C1, which represents the conversation with a friendly virtual human confederate (condition 1) and C2, which represents the conversation with an unfriendly virtual human confederate (condition 2).

4.3.5 Measurement

The measurements for this study include haemodynamic changes within the DLPFC, haemodynamic changes within the MPFC (both measured with the fNIRS) and subjective impression of likeability as captured by the likeability section of the Godspeed questionnaire set.

4.3.6 Tools

The tools adopted in administering this study include a wearable neuroimaging tool; the Functional Near-Infrared Spectroscopy (fNIRS) has been adopted throughout the PhD. We have also utilised a virtual reality head-mounted display, the Oculus Rift DK2; however, this oculus rift has been modified to fit just beneath the fNIRS sensors (Figure 10).

A high graphics power laptop computer has been adopted to run the VR simulation. Throughout the PhD, an Alienware 15 was used. The higher the graphics power of the computer utilised the lower the animation lag within the VR simulation.

The Godspeed questionnaire was used to capture participants' perception of the likeability of our virtual human confederates.

Figure 10 Oculus Rift DK2 adapted for this study

4.3.7 Participants

N = 20 healthy participants undertook a within-study design experiment. Healthy here represent volunteers who have not been diagnosed with any form of cognitive impairments or mental deficits in the past, have not been treated or have a conviction for excessive anti-social behaviour and have not had previous episodes of epilepsy. Participants were between 25 and 42 years old; twelve were male and eight females. None of the participants had taken part in any previous pilot within the group. A previous experiment within the group (Landowska, Roberts, Eachus, & Barrett, 2018) had an effect size of 0.48 for fNIRS measurement of PFC in response to evocative virtual stimuli. Assuming a two-tailed 5% error rate and 80% power suggests the need for 6 participants per condition. However, there is yet to be consensus on how to determine the sample size for fNIRS (Landowska, Roberts, et al., 2018). Moreover, previous similar neuro-imaging studies have used sample size within the ranges of 15 and 20 (Schilbach et al., 2006a; Schroeter, Kupka, Mildner, Uludağ, & von Cramon, 2006; Suzuki, Miyai, Ono, & Kubota, 2008).

Meanwhile, we also attempted to calculate the sample size for this study using G*Power. With an effect size of 0.8, error probability of 0.05 and a Power value of 0.5 and 2 predictors, we arrived at a sample size of 6 participants. Our values were chosen following Cohen's suggestions (Cohen, 1992; Thalheimer & Cooks, 2002). A high effect size of 0.8 was chosen because the effect size would need to be large enough to be visible using NIRSLab (our chosen tool for data analysis) for SPM level 2 analysis. A Power value of 0.5 has also been chosen since this is the first study of this kind and as such the probability that the test will reject a false null hypothesis is kept at 50% which is rather low compared to the generally accepted values. This presents a weak argument for sample size calculation and will benefit from further investigation in the future. This result, albeit weak (alongside the results from previous experiments within the group), suggests that a study with N = 6 participants sufficiently satisfies the sample size requirement of the study. This value remained valid even after participants were split into gamers and non-gamers as none of the two groups had a sample size less than 6. It can be argued that the choice of parameter values for the power analysis could have benefited from a more pragmatic approach. The absence of this suggests a likelihood of under-powered samples. Studies in this domain may benefit from subsequent attempts focusing on power analysis for similar neuro-imaging experiments.

We targeted "healthy" volunteers from within and outside the University. Emails were sent to participants through the departmental offices as well as advertisements on social media. We targeted volunteers within Manchester to avoid excessive travel. There were no specific interests in ethnicity, demographics or cultural orientation of our subjects. However, we ensured participants were above the age of 18.

4.3.8 Procedure

The participant was welcomed and in line with ethical and health/safety procedures, was provided with a consent form and participant information sheet and allowed fifteen minutes to complete this former. Information on participants' prior experience with VR and gaming was captured informally and participants were grouped as G1 and G2. G1 representing participants that had prior experience with VR and gaming and G2 representing participants with no prior experience to VR and gaming.

This grouping was not part of the initial procedure. However, during piloting, and previous demonstrations in science fairs, we observed a difference in participants' behavioural pattern based on prior exposure to VR simulation. The group with little or no experience with VR showed higher excitement trying out the simulation while the other group showed less excitement and were more critical of the simulation (based on their experience with other simulations).

The Hayling sentence completion task was first administered. The administration of the Hayling task followed the procedural guidelines suggested as reported by Burgess and Shallice (1997). Participants were presented with fifteen incomplete sentences in two different sections. In the first section, they were required to complete the sentences with a word or phrase that makes sense in the first section, and a nonsense word or phrase in the second section. The incomplete sentences were read out by the researcher and response time between the end of the incomplete sentence and the response from participants was recorded on a stopwatch. After the Hayling task, the VR headset was put on the participant and a familiarization period for the virtual condition followed. Participants were only asked to look around and get familiar with the virtual environment. During this period, the participants explored the VR environment to eliminate excitement arising from immersion in VR. During the familiarization period, our participant was not required to wear the fNIRS as we were not interested in measuring the neural activity at this stage. Moreover, neuroimaging caps are not particularly comfortable. As a result, we attempted to keep the length of time for which the fNIRS was worn by our participant at a minimal. Familiarization lasted for at most, two minutes. We decided on a fixed maximum time-period for familiarization during initial piloting. During initial piloting, we allowed participants to notify us when they felt okay with familiarizing with the environment, and this process was timed. All participants completed this process in less than two minutes, hence the decision to keep familiarisation at a maximum of two minutes.

Once familiarization was completed, the NIRSport was worn by the participant. A *baseline* for PFC activity was taken where the participants were advised to attempt to do nothing for twenty seconds at the beginning of each condition. The experimental conditions followed baseline sampling (Figure 11). Each condition of the experiment lasted for approximately three minutes, bringing the entire experiment to approximately ten minutes.

At the end of the experiment, participants were asked to fill out the Godspeed questionnaire which captures measures on a 5-point Likert scale. The focus was on the Likeability section of the Questionnaire which measures five properties: Likeness, Friendliness, Kindness, Pleasantness and Niceness. Other sections of the questionnaire series, Anthropomorphism, Animacy and Perceived intelligence were also captured. The outcome of results from these sections would only validate or invalidate the equivalence of the virtual human confederates in both conditions. The participants were also interviewed informally to capture possible findings not targeted by the questionnaire. Video recordings were also taken of each participant to analyse and report any unusual gestures from participants during the experiment.

4.3.9 Method of Data Analysis

Here we report the analysis of data generated from brain imaging and questionnaire. Non-verbal communication, captured from video, is left for another paper. A quantitative approach is taken.

Quantitative Data Analysis

Response time was recorded for each of the sentences of the Hayling sentence completion task. The response times (which was considerably higher in the second section for all participants) was correlated with SPM level 2 readings from the conversational task.

Functional brain imaging data were analysed using NIRSLab Software (which uses statistical parametric mapping and general linear model analysis). We utilized statistical parametric mapping (SPM) approach to compute hemodynamic responses of the brain. All participants brain imaging data were analysed together initially, and analysis was split across G1 and G2 as described earlier.

Questionnaire data were analysed using SPSS. Changes in perception of behaviour and opinions of the virtual humans were calculated using the Wilkinson’s signed ranked test.

Signal Quality, Signal to Noise Ratio (SNR) and interference was monitored using NIRStar to validate the quality of data captured by the fNIRS. Raw data were converted to changes in haemoglobin concentration using the modified Beer-Lambert law (Delpy et al., 1988) for each condition and participant. Oxy (HbO), deoxy (HbR) and total (HbT) haemoglobin time series were band-pass filtered with a low cut-off frequency 1/T for each participant and high cut-off frequency of 0.2Hz to remove drifts, respiration and cardiac effects from data (Piper et al., 2014; Naseer and Hong, 2015). T, as specified for the low cut-off frequency, represents the longest time spent on either condition by each participant.

Figure 11 Participant during Study1

4.4 Results and Discussion

4.4.1 Introduction

The suffixes 1 and 2 have been added to the experimental conditions to indicate condition1 and condition2. C1 and C2 shall also be used to represent condition 1 and condition 2 respectively. This convention is applied to similar cases throughout the rest of the paper.

The results of the Godspeed questionnaire (Likeability section) is presented first. This result establishes if participants find one virtual confederate (C1) friendlier than the other (C2), which is necessary to validate the approach fNIRS results are also presented.

4.4.2 Results

Godspeed Questionnaire (Likeability Section) data

All twenty participants completed the experiment and filled out the Godspeed questionnaire.

A Wilcoxon Signed Ranks Test showed that participants liked the friendly virtual human confederate more, p approximates to 0.00003, Table 3. Figure 12 shows the mean value of the participants' ratings.

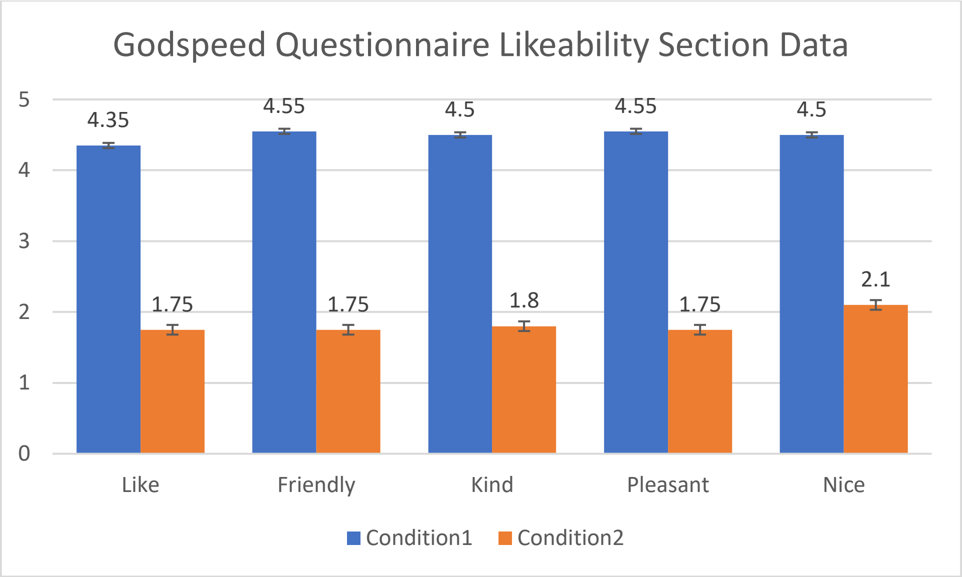


Figure 12 Descriptive Statistics for Godspeed questionnaire (Likeability section) data

	Like	Friendly	Kind	Pleasant	Nice
Z	-4.006^b	-4.006^b	-3.867^b	-3.966^b	-3.880^b
Significance	0.00003	0.00002	0.00003	0.00002	0.00004

Table 3 Wilcoxon Signed Ranks Test Result for Godspeed questionnaire data.

Functional Near-Infrared Spectroscopy (fNIRS) data

An initial analysis was carried out using the default lower band filter provided by the NIRSLab, software for analysing fNIRS data. This is explained in section 3.7. As a result of this, 10 of our participants' readings were excluded as noisy data. A paired sample t-test was carried out on the remaining 10 participants' data. The result is provided in Appendix 9. Following this high exclusion rate which we initially attributed to the cumbersomeness of the equipment (the oculus rift and the fNIRS), a second study was planned which was aimed at carrying out the same experiment using a less cumbersome (a 50-inch screen) and comparing the results, hence our second study.

However, feedback from reviewers on a submitted publication by Aleksandra Landowska within the group suggested that the lower bandpass filter adopted in this analysis was wrong because it was based on an assumption that the experimental condition lasted for 100 seconds and therefore was fixed at a value of F=1/T where F is the low bandpass frequency and T is the time in seconds. These values were corrected, albeit after the second study had been carried out.

Following the corrected low bandpass filter values, one of our (N = 20) participants were excluded due to a complete absence of data for condition2. Leaving us with (N = 19) participants.

SPM level 1 analysis showed significant activation in both conditions compared to baseline for each of the (N = 19) participants. This activation appeared to be higher in C1 for some participants and higher in C2 for others. Also, the activation was observed in the medial prefrontal cortex (MPFC) in some participants and the dorsolateral prefrontal cortex (DLPFC) in other participants.

SPM level 2 analysis, however, failed to show statistically significant activation in any of the conditions. Activation here refers to increased oxygenation within the prefrontal cortex.

Further analysis of the (N=19) participants along the lines of G1 and G2 was undertaken; where G1 represents participants with prior experience of VR and gaming (N=7) and G2 represents participants with no prior experience of VR and gaming (N=12). The number of participants in each category met the sample size criteria as calculated using G*Power and previous calculations within the group.

G1 – participants with prior experience on VR and gaming

SPM Level 2 analysis showed a statistically significant higher activation ($p<0.05$) within the left medial PFC (lMPFC) during C1 compared to C2 (Figure 13)

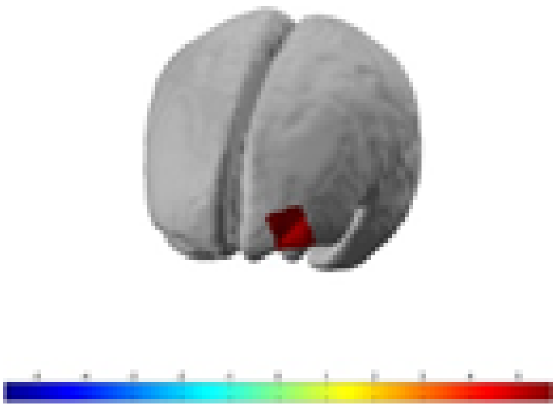


Figure 13 SPM Level2 analysis for participants with prior experience with VR and gaming

G2 – participants with no prior experience on VR and gaming

SPM Level 2 analysis showed a statistically significant higher activation in left dorsolateral PFC (lDLPFC) during C2 compared to C1 (Figure 14).

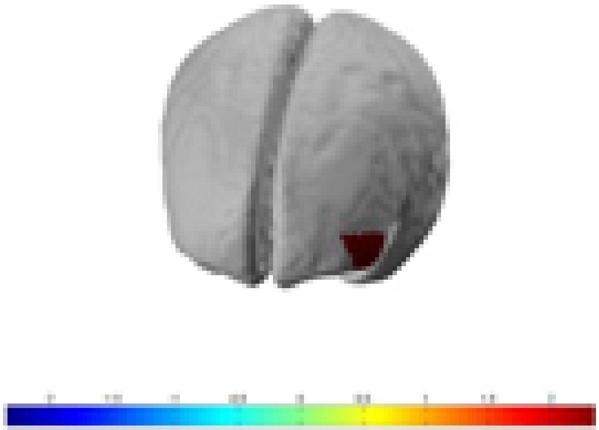


Figure 14 SPM Level2 analysis for participants without prior experience with VR and gaming

We reject the null hypothesis for H2 only for G2. Participants that fall into this category showed an increase in activity in the DLPFC when the conversation was taken over by an unfriendly virtual confederate.

Hayling Task

The Hayling task was conducted in this experiment to compare the outcome of the neuro-imaging task to the Hayling task which is a known test of inhibition. At the time of designing this study, we did not see a reason to capture neural correlates for the Hayling task. Moreover, this would require participants to spend longer time-periods wearing cumbersome devices which is undesirable.

We attempted to score the Hayling task based on the time spent on each question. This is described as the latency of response by the participant subsequently. An attempt was made at correlating this outcome with the SPM data for each condition. Although the outcome of Hayling task was as anticipated (concerning latency of responses), with a mean time M = 70 seconds for the first condition and M = 149 seconds for the second condition, no strong correlation was found between them. This study did not monitor neural response during the Hayling task, consequently, we could not further analyse the outcomes. The full result of this correlation is attached to Appendix 7. Out of a total of sixteen correlations, only one of the records showed a positive correlation between activity in the LDLPFC (Condition 2) and latency during part 2 of our Hayling task, *r* = 0.48, *p* = 0.036. A summary table of this correlation is provided in table 4 where ROI represents the region of interest, r represents Pearson Correlation, p represents significance and N represents the number of participants. This is however not strong enough to suggest a correlation between Hayling task and fNIRS data.

Conversation condition	ROI	Hayling condition	r	p	N
1	LDPFC	H1	-0.0332	0.165	19
1	LDPFC	H2	-0.394	0.095	19
1	RDPFC	H1	-0.0223	0.358	19
1	RDPFC	H2	0.075	0.761	19
1	LMPFC	H1	-0.191	0.432	19
1	LMPFC	H2	0.088	0.720	19
1	RMPFC	H1	0.052	0.883	19
1	RMPFC	H2	0.099	0.687	19
2	LDPFC	H1	-0.077	0.755	19
2	LDPFC	H2	0.484	0.036	19
2	RDPFC	H1	0.088	0.721	19
2	RDPFC	H2	0.353	0.138	19
2	LMPFC	H1	0.113	0.644	19
2	LMPFC	H2	0.258	0.286	19
2	RMPFC	H1	-0.414	0.078	19
2	RMPFC	H2	0.056	0.821	19

Table 4 Correlation between Hayling task and conversation task.

A multivariate analysis of variance was also carried out on this data, which was aimed at comparing the variances in the two conditions of the conversation task to that of the Hayling task. However, no significant value was found with this analysis. The full analysis is reported in Appendix 8. Moreover, the readings for the conversation task was based on erratic parameter value selections for the SPM level 2 analysis, and as a result, the descriptive statistics for the RMPFC was completely absent as it was excluded as noise by NIRSPort. Even though there was no significant outcome found with the MANOVA, we briefly report the outcome below. The mean values for the LDLPFC, RMPFC, LMPFC and RMPFC are 0.0019, 0.0019, 0.0017 and 0.00 respectively. The Wilk's lambda value of the MANOVA are as follows: $F(4, 33) = 0.969$; $P > 0.05$; Wilk's $\wedge=0.895$. This outcome was not further pursued.

4.4.3 Discussion

Our hypotheses are recapped below:

When a conversation with a friendly virtual human confederate is taken over by an unfriendly virtual counterpart,

Godspeed questionnaire data will show participants like the friendly virtual confederate better – H1.

Participants will exhibit an increase in activation of the dorsolateral prefrontal cortex (DLPFC) while conversing with the unfriendly virtual human confederate – H2.

Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) while conversing with the unfriendly virtual human confederate – H3.

Godspeed Questionnaire

The Wilcoxon Signed Ranks Test (WSRT) has been adopted in data analysis because the data is not normally distributed, and the same participants are repeated for both conditions.

The results show statistically significant evidence that participants liked the confederate in C1 better than C2. This is in-line with previous studies involving humans, which suggest that verbal aggressiveness triggers negative emotions (Infante & Wigley III, 1986).

The finding was associated with a strong statistically significant effect, $p < 0.05$. Therefore, the null hypothesis for H1 is rejected. Rejecting the null hypothesis for H1 was key in this study as there would have been no basis for measuring the neural correlates of the emotions triggered by the virtual confederates if the differences between participants' perception of them could not be established.

We did not find the need to split our Godspeed questionnaire analysis along the lines of G1 and G2. This is because descriptive statistics for all participants showed a minimum value of 4 for any of the components of likeability in C1 and a maximum value of 3 for any of the same components for C2 on a 5-point Likert scale. By implication, the outcome of this analysis will remain the same across groups.

We also analysed other sections of the Godspeed questionnaire series. The concept behind this was to investigate if participants impression of the virtual human varied for each condition. Particular attention was paid to the anthropomorphism and animacy sections because these sections are related to the design of the virtual humans. We speculate that a significant difference in participant impression of the virtual humans in any of these sections may invalidate the rest of the findings. A Wilcoxon's signed rank test showed no significant difference ($p<0.05$) in any of the components for either of anthropomorphism or animacy. This eliminates the likelihood of bias resulting from discrepancies in the virtual humans for each condition.

Meanwhile, all the components of the "perceived intelligence" section showed statistically significant evidence ($p<0.05$) that participants perceived the C1 virtual human as more intelligent than the C2 Virtual human. Perceived safety was not investigated as this is suitable for robots.

fNIRS Data

SPM level 2 analysis for G1 showed a statistically significant activation ($p<0.05$) in the medial prefrontal cortex (MPFC) for C1, while G2 showed a statistically significant increase in the DLPFC for C2. This suggests an effect emanating from increased experience with VR and gaming. The effect of gaming on cognitive processes and therapy is gaining increased attention (Brown & Garner, 2016; Paquin, Crawley, Harris, Horton, & rehabilitation, 2016). Literature review shows little evidence of this effect; therefore, our study further contributes to this increasing body of evidence. In line with Brown and Garner (2016), we argue that exposure to gaming and technology, in general, should be a key concept in designing studies aimed at therapies for mental deficits.

The statistically significant increased activation within the MPFC is consistent with studies linking the MPFC to the social brain (Frith, 2007; Olivito, 2017).

Godspeed questionnaire data shows that participants liked the virtual confederate in C1 better than C2; time spent in C1 was also longer than C2 for all participants. This suggests that participants may have been more socially engaged in C1, hence the significant increase in activation in MPFC for G1. This argument ties well with studies that have suggested that people engage less with others when verbal aggression is observed (Infante & Wigley III, 1986). Furthermore, the MPFC is also associated with working memory (Euston et al., 2012; Goldin et al., 2008; Ridderinkhof et al., 2004). We opine that working memory involvement may have been enhanced due to the higher social engagement inspired by the higher perceived friendliness in C1.

The significantly increased activation in C1 may have also come from these participants' getting used to being immersed in the VR. Perhaps, allowing longer time-period for the familiarization stage may have eliminated effects resulting from this initial immersion; however, the cumbersomeness and discomfort of the adapted Oculus Rift DK2 made this impractical. Moreover, the fact that activation was higher in C2 for other participants (which represents a higher number) makes immersion less likely responsible for this behaviour.

SPM Level 2 analysis for G2 (N=12) showed significant activation in the dorsolateral prefrontal cortex activity in C2.

The findings are in line with previous studies (Shackman, McMenamin, Maxwell, Greischar, & Davidson, 2009) as C2 (which presented a higher need for behavioural regulation) showed a significant increase in the DLPFC The MPFC failed to show a significant increase in activation; however, Gusnard and colleagues (2001) argue that the MPFC is among the regions that exhibit decreases from baseline across a wide variety of goal-driven tasks especially attention-demanding and explicit self-referential tasks. However, although the measured neural activity within the MPFC like most regions of the PFC may suggest the involvement/non-involvement of this region in cognitive activity, it is usually not sufficient to suggest it as a proxy for these activities. The decrease in MPFC activity in C2 compared to C1 suggests that MPFC activation may be attenuated by some organized brain function for this experimental task. However, this conflicts with our results for G1 which showed increased activity in the MPFC albeit in C1 instead of C2 where we expected increased activity. We speculate that experience with technology (VR in this case) may be implicated in this finding, but we are unclear to what extent this factor impacts on the outcome. This is outside the scope of this study and is therefore not investigated further.

G1 analysis only showed a significant increase in activation (p<0.05) within the MPFC in C1. We seek to reject the null hypothesis for an increase in C2 instead. Therefore, we reject the null hypothesis for H3.

G1 also failed to show a significant increase in activation (p<0.05) within the DLPFC in any condition thus we fail to reject the null hypothesis for H2.

Meanwhile, G2 analysis was associated with a statistically significant effect in the DLPFC; therefore, we reject the null hypothesis for H2 for G2.

We were unable to show any statistically significant effect (p<0.05) in the MPFC, or otherwise answer for any attenuation to this effect, we, therefore, fail to reject the null hypothesis for H3.

4.5 Conclusion

This study was aimed at investigating if virtual humans can trigger measurable neural responses indicative of inhibition in humans during a conversation.

An experiment was carried out involving two different virtual human confederates, one attempting to hold a friendly conversation and the other attempting to hold an unfriendly conversation. Friendliness of virtual human confederates was measured using the likeability section of the Godspeed Questionnaire series. The experiment was carried out using a virtual reality head-mounted display (HMD) and the functional near infrared spectroscopy (fNIRS) to measure brain response. Since the fNIRS is suitable for measuring activity within the prefrontal cortex (PFC), we focused on PFC regions that have been implicated in previous studies involving social interaction and inhibitory response, the medial prefrontal cortex (MPFC) and the dorsolateral prefrontal cortex (DLPFC).

A Wilcoxon’s signed rank test of the likeability section of the Godspeed questionnaire showed that participants liked the friendly virtual human confederate better than the unfriendly one. We, therefore, reject the null hypothesis for H1. Rejecting the null hypothesis for H1 was the basis for proceeding with the fNIRS data analysis.

SPM level 2 of fNIRS data failed to show any significant increase in activation within either the DLPFC or MPFC; therefore, we fail to reject the null hypothesis for H2 and H3.

Meanwhile, during an initial briefing, information on participants prior exposure to VR and gaming was captured verbally. Participants were then split into two groups: G1 (N=7) representing those with prior experience with VR and gaming and G2 (N=12) representing those without prior experience with VR and gaming.

Subsequent analysis along the lines of G1 and G2 was unable to show enough evidence to reject the null hypothesis for H2 and H3 for G1. However, we observed a statistically significant decrease within the MPFC when the conversation moved to the unfriendly virtual human confederate.

G2, on the other hand, showed a statistically significant increase within the DLPFC during the conversation with the unfriendly virtual human. We, therefore, reject the null hypothesis for H2. There was no statistical significance in MPFC activity of G2, therefore we fail to reject the null hypothesis for H3.

CHAPTER 5

STUDY 2 – LARGE SCREEN DISPLAY

5.1 Introduction

This study, Study 2 employs the use of a 50-inch Samsung monitor instead of the oculus rift adopted in Study 1. Initial SPM Level 2 analysis of Study 1 using the NIRSLab failed to show any statistically significant result. This was partly because of a significant exclusion of noisy data due to the cumbersomeness of the equipment and an erratic adoption of filter parameters for data analysis within NIRSLab as reported in the previous chapter. A paired sample t-test on each Region of Interest (ROI), the dorsolateral prefrontal cortex (DLPFC) and the medial prefrontal cortex (MPFC), using the same filter, however, showed a significant effect on the left DLPFC and the left and right MPFC. This was achieved after the exclusion of half of the functional near infrared spectroscopy (fNIRS) data due to empty result values. It was therefore imperative to further validate the authenticity of the results from Study 1 with a similar study in which the cumbersomeness of equipment was reduced. This is because cumbersomeness was identified as the reason for the data loss witnessed in Study 1. Experimental design and procedure remain the same as Study 1 except for the fact that fNIRS data was captured during the Hayling task in this study. This study is aimed at evoking a neural response indicative of inhibition in humans engaged in conversations with virtual humans using a large screen on one hand and comparing the responses evoked in this study with Study 1 on the other hand. Furthermore, the study also compares the outcomes of the Hayling task with that of the conversational tasks.

5.2 Scope

The scope of this study is the same as that of Study1 as reported in Chapter 4, Section 4.2.

5.3 Methodology

5.3.1 Overview

N=10 healthy participants took part in a within-subject design experiment, where they conversed on an emotive subject with a friendly virtual human on one hand, and an unfriendly virtual human on the other hand. Participants also carried out a Hayling sentence completion task before the conversation task.

All experimental design and procedure have been carried out as approved by the University of Salford, Research, Innovation and Academic Engagement Ethical Approval Panel with approval number -HSR1617-90. This was an amendment of the approval received for Study1.

5.3.2 Task

Participants were engaged in a simulation of a public bar. They were then asked to hold a conversation with virtual human confederates in turn. The conversation was centred on Brexit and the General elections. The conversation was the same for both conditions. Aside from holding a conversation with the virtual human confederates, participants were given no other instructions or goals other than to suppress any anti-social or socially antagonistic behaviour during the experiment (where necessary) and instructions on how to stop the experiment if they wished. The justification for the choice of topic and potential limitation is captured in the previous chapter.

5.3.3 Hypothesis

When a conversation with a friendly virtual confederate is taken over by an adversarial virtual counterpart,

Godspeed questionnaire data will show participants like the friendly virtual confederate better – H1.

Participants will exhibit an increase in activation of the dorsolateral prefrontal cortex (DLPFC) – H2.

Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) – H3.

This study was aimed at comparing the fNIRS data in Study1 and Study2. This suggests a fourth hypothesis which is peculiar to this study:

fNIRS data for both studies will show no significant difference in ROI activation form conversational task – H4.

Meanwhile, since the Hayling task is a known paradigm for investigating inhibition, we attempted to show similarities between fNIRS data resulting from Hayling task and that resulting conversational task in the experiment. Following this, a fifth hypothesis, which is based on a null hypothesis is proposed:

fNIRS data for Hayling task and the conversational task will show no significant difference in ROI activation – H5.

5.3.4 Variables

The variables remained the same as Study 1.

The dependent variables include the likeability of virtual human confederate (measured using the Godspeed questionnaire), DLPFC activation and MPFC activation.

The independent variable is the friendliness of the virtual human confederate. Like Study 1, we adopted the convention C1 to represent conversation with a friendly virtual confederate (condition 1) and C2 to represent a conversation with an unfriendly virtual human confederate.

5.3.5 Measurement

The measurements remained the same as Study 1. They include haemodynamic changes within the DLPFC, haemodynamic changes within the MPFC, subjective impression of likeability as captured by the likeability section of the Godspeed questionnaire set.

5.3.6 Tools

Apart from a change in display medium, the tools adopted in this study largely remained the same as Study 1.

The tools include a wearable neuroimaging tool - Functional Near-Infrared Spectroscopy (fNIRS), a computer running VR and allow control of VR by an operator, a standard Godspeed questionnaire and a Samsung 50-inch display monitor (Figure 3).

5.3.7 Participants

N = 10 participants undertook a repeated measure design experiment. This number has been justified in Chapter 4, Section 4.3.7. Participants were between 19 and 28 years old; six were male and four females. None of the participants had taken part in any previous pilot within the group. We targeted “healthy” volunteers within and outside the University. Healthy here represent volunteers who have not been diagnosed with any form of cognitive impairments or mental deficits in the past and have not been treated or have a conviction for excessive anti-social behaviour. Emails were sent to participants through the departmental offices as well as advertisements on social media. We targeted volunteers within Manchester to avoid excessive travel. There were no specific interests in ethnicity, demographics or cultural orientation of our subjects. However, we ensured participants were above the age of 18.

5.3.8 Procedure

The participant was welcomed and in line with ethical and health/safety procedures, was provided with a consent form and participant information sheet and allowed fifteen minutes to complete this former. As reported in the previous chapter, Information on participants' prior experience with VR and gaming was captured informally and participants were grouped as G1 and G2. G1 representing participants with prior experience with VR and gaming and G2 representing participants with little or no prior experience with VR and gaming.

The logic behind this grouping of participants is detailed in the Procedure section of the previous chapter.

The NIRSport was worn by the participant for the administration of the Hayling task. A *baseline* for PFC activity was taken where the participants were advised to attempt to do nothing for twenty seconds at the beginning of each condition. the experimental conditions followed baseline sampling and each condition lasted for approximately one minute for each participant. The Hayling task was administered in the same way it was administered in the first study (described in the procedure section of the previous chapter). However, unlike the first study where response times was recorded, in this study, the time for each of the sections of the Hayling task was recorded for each participant. The times here were recorded for SPM analysis of the Hayling task performance. The conversational task followed the Hayling task and the procedure remained the same with the first study (Figure 15). Each condition of the experiment lasted for approximately three minutes, bringing the entire experiment to approximately twelve minutes.

At the end of the experiment, participants were asked to fill the Godspeed questionnaire aimed at capturing their impression of the virtual human. The participants were also interviewed informally to capture possible findings not targeted by the questionnaire.

Figure 15 Participant during Study2

5.3.9 Method of Data Analysis

For this study, the fNIRS was worn by participants during the Hayling sentence completion task, therefore data analysis for the Hayling task was not based on response time. Data analysis for the Hayling task was carried out similarly to the conversational task and results compared. Apart from this, everything else remained the same as in the previous chapter.

Please see Chapter 4, Section 4.3.9.

5.4 Results and Discussion

5.4.1 Introduction

The suffixes 1 and 2 have been added to the experimental conditions to indicate condition1 and condition2. C1 and C2 shall also be used to represent condition 1 and condition 2 respectively. This convention is adopted throughout the thesis.

The results of the Godspeed questionnaire (Likeability section) is presented first. This result establishes if participants find one virtual confederate (C1) friendlier than the other (C2). fNIRS results are also presented.

5.4.2 Results

Godspeed Questionnaire (Likeability Section) data

All ten participants completed the experiment and filled out a standard Godspeed Questionnaire which captures measures on a 5-point Likert scale (Figure 16). The focus was on the Likeability section of the Questionnaire which measures five properties: Likeness, Friendliness, Kindness, Pleasantness and Niceness (Table 5).

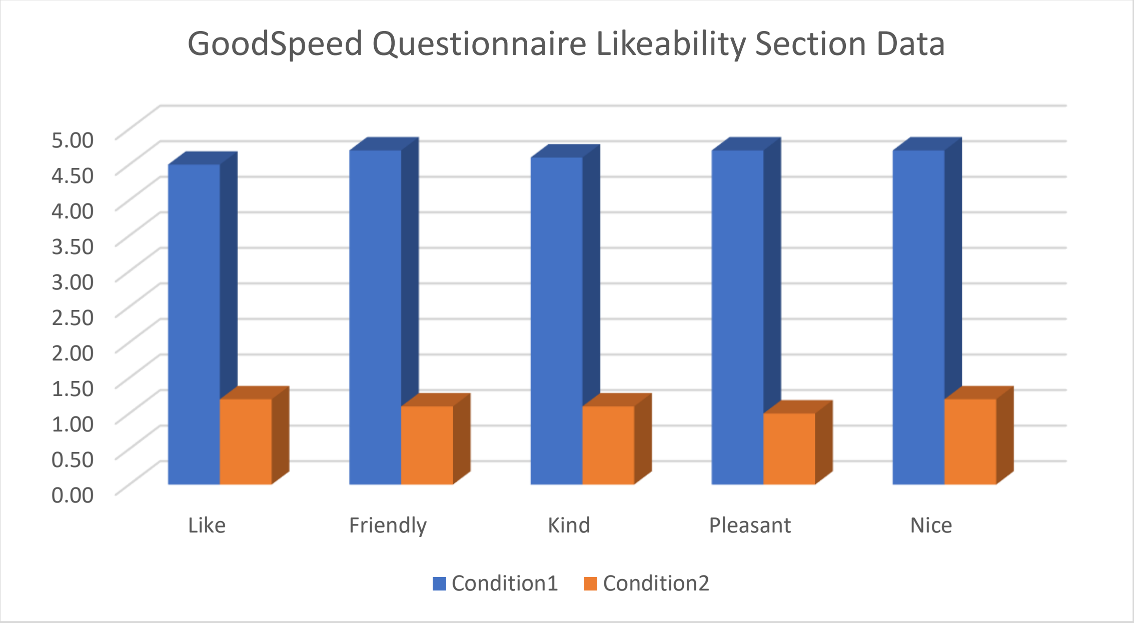


Figure 16 Descriptive Statistics for Godspeed questionnaire (Likeability section) data

	Like	Friendly	Kind	Pleasant	Nice
Z	-2.859^{b}	-2.889^{b}	-2.913^{b}	-2.919^{b}	-2.913^{b}
Significance	0.0042	0.0039	0.0036	0.0035	0.0036

Table 5 Wilcoxon Signed Ranks Test Result for Godspeed questionnaire data.

Functional Near-Infrared Spectroscopy (fNIRS) data

All (N=10) participants were included in this analysis.

An initial analysis was carried out using the same lower bandpass filters that were adopted initially in Study1. SPM level 2 analysis and subsequently ROI analysis failed to show statistically significant evidence of change in PFC activity in any of the ROIs. This analysis was imperative to achieve the purpose of the present study.

Meanwhile, the analysis was also carried out using corrected bandpass filters. SPM level 1 analysis showed significant activation in both conditions compared to baseline for each of the (N = 10) participants. This activation appeared to be higher in C1 for some participants and higher in C2 for others. Activation varied from the medial prefrontal cortex (MPFC) to dorsolateral prefrontal cortex (DLPFC) across participants.

SPM level 2 analysis, however, failed to show statistically significant activation in any of the conditions. Activation here refers to increased oxygenation within the prefrontal cortex.

Further analysis of the (N=10) participants along the lines of G1: participants with prior experience of VR and gaming (N=6) and G2: participants with no prior experience of VR and gaming (N=4) was undertaken.

G1 – participants with prior experience on VR and gaming

SPM Level 2 analysis showed a statistically significant higher activation ($p<0.05$) within the MPFC and DLPFC during C1 compared to C2 (Figure 17).

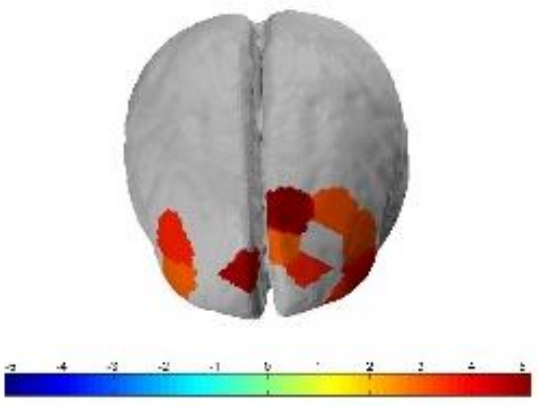


Figure 17 SPM Level2 analysis for participants with prior experience with VR and gaming

G2 – participants with no prior experience on VR and gaming

SPM Level 2 analysis showed statistically significant higher activation in right MPFC during C1 compared to C2 (Figure 18).

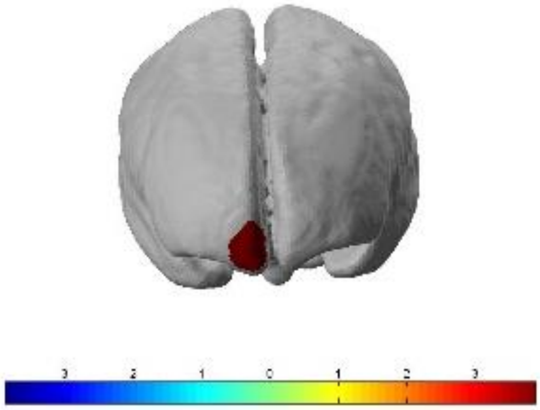


Figure 18 SPM Level2 analysis for participants without prior experience with VR and gaming

Following this, we, therefore, reject the alternate hypothesis for H2 and H3.

5.4.3 Discussion

The hypotheses are recorded in section 5.3.3.

Godspeed Questionnaire

Like Study1, the Wilcoxon Signed Rank Test (WSRT) has been adopted in data analysis because the data is not normally distributed, and the same participants are repeated for both conditions.

The results show statistically significant evidence that participants liked the virtual confederate in C1 better than C2. This is in-line with previous studies which suggest that verbal aggressiveness triggers negative emotions (Infante & Wigley III, 1986).

The finding was associated with a strong statistically significant effect of approximately p = 0.004. Therefore, the null hypothesis for H1 is rejected. Rejecting the null hypothesis for H1 was key in this study as there would have been no basis for measuring the neural correlates of the emotions triggered by the virtual confederates if the differences between participants' perception of them could not be established.

fNIRS Data

G1 showed a statistically significant activation ($p<0.05$) in the medial prefrontal cortex (MPFC) and the dorsolateral prefrontal cortex (DLPFC) for C1, while G2 showed statistically significant activation in the MPFC for the same condition.

As highlighted in Study 1, the notion of the existence of the social brain of which the MPFC is part of (Frith, 2007; Olivito, 2017) suggest that the increased activation within the MPFC may be linked with higher social engagement with the virtual human confederate in C1. Increased involvement of working memory in C1 is also suggested and thus an increased MPFC activation.

However, since there was no increased activity in C2 compared to C1 for both groups, we, therefore, reject the alternate hypothesis for H2 and H3.

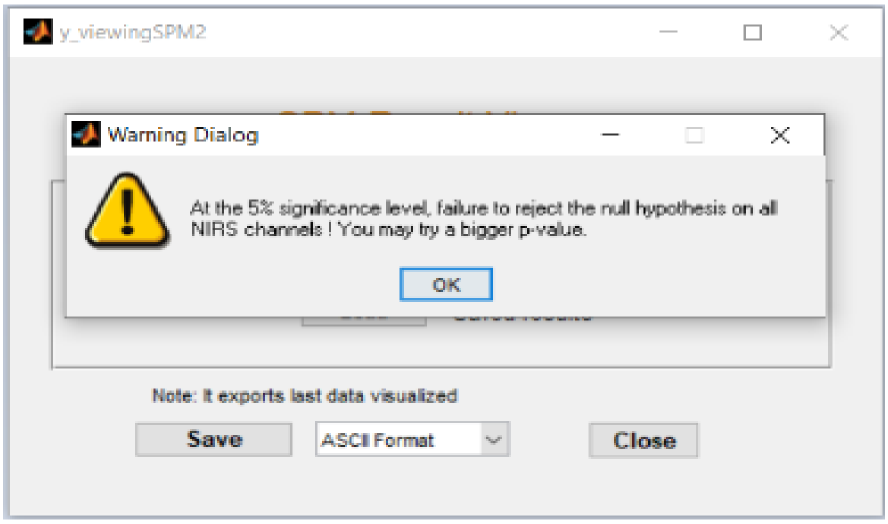
Comparing Study1 and Study2 data

As stated earlier, Study1 data was erratically analysed using the wrong lower bandpass filter value for fNIRS signals. SPM level 2 analysis failed to show statistically significant evidence to reject the null hypothesis, therefore a region of interest (ROI) analysis was carried out on the left and right MPFC and DLPFC, Due to the wrong lower bandpass filter values, approximately half of the data was excluded as noise thus only N=10 participants had valid data. This informed the N=10 participants adopted in Study2. Study2 data were initially analysed using the same filter for uniformity and the results from this analysis were used in comparing the two studies. Study2 data in this context refers to the data from the conversational task.

A multivariate analysis of variance (MANOVA) was carried out on Study1 and Study2 data using two independent variables (study and conditions). With studies being “1” for Study 1 and “2” for Study 2, and conditions as earlier described. The MANOVA showed no significant difference between the data from the two studies. Thus, we reject the null hypothesis for H4.

Hayling task data

Although the Hayling task is a known paradigm for investigating inhibition, SPM Level 2 analysis failed to show a significant increase in activation within the PFC in any of the conditions.



At the 5% significance level, failure to reject the null hypothesis on all NIRS channels ! You may try a bigger p-value.

Note: It exports last data visualized

Figure 19 SPM Level2 analysis for Hayling task data

The analysis showed no significant increase in brain activity in any of the NIRS channels at the 5% significance level ($p<0.05$) as shown in Figure 19. The implication of this for this study is discussed later. A paired sample t-test on the ROI data also failed to show any significant activation in any of the regions.

The purpose of capturing fNIRS data during the Hayling task was to compare the outcome with that of the conversational task. Therefore, a MANOVA was carried out on these tasks using two independent variables, task and condition. With tasks being “1” for the conversational task and “2” for the Hayling task and conditions being as earlier described. The MANOVA showed no significant difference between data from the two tasks (Appendix 8). Thus, we accept the null hypothesis for H5.

5.5 Conclusion

In summary, findings showed that participants liked the friendly virtual human confederate better than the unfriendly one. This was measured using the likeability section of the Godspeed Questionnaire. We, therefore, reject the null hypothesis for H1. Rejecting the null hypothesis for H1 was the basis for proceeding with the fNIRS data analysis

Meanwhile, Participants were split into two groups; G1: (N=6) participants who had prior experience with VR and gaming, and G2: (N=4) participants who had no prior experience with VR and gaming. Our study was unable to show enough evidence to reject the null hypothesis for H2 and H3 for either G1 or G2, hence we reject the alternate hypothesis for H2 and H3.

Although the data for Study1 had been wrongly analysed as stated earlier, one assumption of the current study is that both studies will produce equivalent outcomes if the same filters are applied. Applying the same filters on Study2 and carrying out a MANOVA attempted to justify this assumption. A MANOVA carried out on studies 1 and 2 using two independent variables (Study and Condition) failed to show any statistically significant difference between data from the two studies; we, therefore, accept the null hypothesis for H4. The premise on which these assumptions are made are weak however as other factors which may include the wrong bandpass filters could be responsible for this outcome.

Meanwhile, a MANOVA carried out on data from the conversational task and the Hayling task using two independent variables (Task and Condition) in Study2 also failed to show a statistically significant difference between data from the tasks. Therefore, we accept the null hypothesis for H5. The Hayling and conversational tasks in Study2 were compared using the correct low bandpass filters. Both SPM Level 2 and ROI analysis failed to show a statistically significant increase across conditions for both tasks. Just like with H4, H5 is based on weak assumptions and the absence of statistical significance between the result for these tasks may only be consequent to other factors which are outside the scope of this study. Previous Hayling task experiments have only suggested significant effects in subjects with frontal lobe lesion compared to subjects with lesions in other regions (Burgess & Shallice, 1996). This may account for the failure of our “healthy” participants to show statistically significant differences in neural basis between the two conditions (condition1 and condition2) of the Hayling task. Healthy here referring to participants with no prior diagnoses of cognitive impairments, condition1 referring to the group of tasks where participants complete the sentences with words or phrases that make sense and condition2 referring to the group of tasks where participants complete the sentences with words or phrases that do not make sense.

The MANOVA on data from the conversational task and the Hayling task suggests a similarity between PFC activity evoked by these two tasks. In the course of literature review, we did not find any study that attempted to compare the neural activity during a known paradigm for measuring executive functioning to the neural activity during a natural activity such as social interaction. This study attempts to fill this gap. However, a significantly higher number of participants would have presented a stronger argument.

CHAPTER 6

STUDY 3 – IMMERSIVE SUITE

6.1 Introduction

This study follows two previous studies, Study1 which adopted a Virtual Reality Head Mounted Display (HMD) and Study2 which adopted a large 50-inch screen. Both studies investigated neural responses in participants during conversations with virtual humans. Neural correlates were captured using the functional near infrared spectroscopy (fNIRS). A high data exclusion rate as a result of the cumbersomeness of the equipment on participants in Study1 suggested the need for a second study (Study2) which adopted a less cumbersome approach. Although Study2 presented a significantly increased data inclusion rate and comparison with Study1 (using a MANOVA) showed no statistically significant differences between the outcomes, a third study (Study3) was sought which harnesses the strengths of both studies with increased rigour and design quality.

The first two studies used different virtual human confederates for each condition and maintained the same order for all participants. One may argue that participants may have perceived the virtual humans differently and consequently, this may have impacted the results. Meanwhile, it is unclear whether the constant order maintained in the experimental conditions affected the outcome of the results. These arguments question the rigour of the methods adopted in the first two studies. Moreover, previous examiners also highlighted the need for this study.

This study was carried out with increased rigour. The same virtual human confederate was used for each condition in this study, and the experimental conditions were counterbalanced across participants to eliminate questions along these lines of the arguments raised in the first two studies. The experiment was carried out within an immersive suite with a large display screen for the virtual humans and two adjacent projections to enhance immersion. This display system attempts to retain the immersion of Study1 and the reduced cumbersomeness of Study2. Loomis and colleagues (1999) highlighted the advantages of immersion in attaining experimental control and ecological validity. Loomis and colleagues (1999) suggested that under normal circumstances, a trade-off is inevitable between ecological validity and experimental control. However, they argued that immersive virtual environments (IVE) offer an improved perception of virtual objects and ultimately strikes a balance between experimental control and ecological validity with a minimal trade-off. Generally, ecological validity requires immersion, therefore, immersion is a key consideration of this study. The immersion within Study1 was via a head-mounted display, here, it was via projection onto walls and floor of a clinic like space.

Meanwhile, Study2 participants did not complain about device cumbersomeness as was the case with Studw1, therefore, we attempt to replicate this in the current study by ensuring that only the fNIRS is worn by the participants. The outcome of this study represents the main findings of this research.

6.2 Scope

The scope of this study is the same as that of Study1 as reported in Chapter 4, Section 4.2.

6.3 Methodology

6.3.1 Overview

N=14 healthy participants took part in a within-subject design experiment, where they conversed on an emotive subject with a virtual human which played a neutral but friendly role in one condition and an unfriendly role in another condition.

All experimental design and procedure have been carried out as approved by the University of Salford, Research, Innovation and Academic Engagement Ethical Approval Panel with approval number -HSR1617-90.

6.3.2 Task

Participants were engaged in a simulation of a public bar. They were then asked to hold a conversation with a virtual human confederate which plays a friendly role in one condition and an unfriendly role in another condition. The conditions in the study were counter-balanced such that the conversation with the friendly virtual human confederate was condition1 while the conversation with the unfriendly virtual human confederate was condition2 for N=7 participants and vice versa for the remaining N=7 participants. Like the previous two studies, the conversation was centred on Brexit and the General elections and was the same for both conditions. Aside from holding a conversation with the virtual human confederate, participants were given no other instructions or goals other than to suppress any anti-social or socially antagonistic behaviour during the experiment (where necessary) and instructions on how to stop the experiment if they wished. The justification for the choice of topic and potential limitation is captured in the previous chapter.

6.3.3 Hypothesis

Godspeed questionnaire data will show participants like the friendly virtual confederate better – H1.

Participants will exhibit increased activation of the dorsolateral prefrontal cortex (DLPFC) while conversing with the unfriendly virtual human confederate – H2.

Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) while conversing with the friendly virtual human confederate – H3.

6.3.4 Variables

Variables remained the same as Study 1.

The dependent variables for this study are the likeability of virtual confederate (measured using the Godspeed questionnaire), DLPFC activation and MPFC activation.

While the independent variables are the friendliness of the virtual human confederate. We chose the conventions C1 to represent the conversation with a friendly virtual human confederate (condition 1), and C2 to represent the conversation with an unfriendly virtual human confederate (condition 2).

6.3.5 Measurement

The measurements remained the same as Study 1; which includes: haemodynamic changes within the DLPFC, haemodynamic changes within the MPFC and subjective impression of likeability as captured by the likeability section of the Godspeed questionnaire set.

6.3.6 Tools

The tools remained the same as the first two studies and they include a wearable neuroimaging tool - Functional Near-Infrared Spectroscopy (fNIRS), a computer running VR and allow control of VR by an operator, a standard Godspeed questionnaire.

For this study, the chosen environment is the Immersive suite located in Mary Seacole Building, University of Salford, Manchester. (Figure 4).

6.3.7 Participants

N = 14 participants undertook a repeated measure design experiment. Previous similar neuro-imaging studies have used sample size within the ranges of 7 and 20 (Schilbach et al., 2006a; Schroeter et al., 2006; Suzuki et al., 2008). To justify this sample size, we have also added evidence to sample size calculation within the group in section 4.3.7.

Participants were between 18 and 31 years old; nine were male and five females. None of the participants had taken part in any previous pilot within the group. We targeted "healthy" volunteers within and outside the University. Healthy here represent volunteers who have not been diagnosed with any form of cognitive impairments or mental deficits in the past and have not been treated or have a conviction for excessive anti-social behaviour. Emails were sent to participants through the departmental offices as well as advertisements on social media. We targeted volunteers within Manchester to avoid excessive travel. There were no specific interests in ethnicity, demographics or cultural orientation of our subjects. However, we ensured participants were above the age of 18.

6.3.8 Procedure

The participant was welcomed and in line with ethical and health/safety procedures, was provided with a consent form and participant information sheet and allowed fifteen minutes to complete this former.

Simulation software was played, and participants were allowed to familiarise themselves with the environment. The logic behind this familiarisation stage is detailed in the Procedure sections of the previous two chapters. Then the NIRSport was worn and a *baseline* for PFC activity was taken where the participants were advised to attempt to do nothing for twenty seconds at the beginning of each condition. The experimental conditions followed baseline sampling (Figure 20) and each condition lasted for approximately (often less than) three minute for each participant, bringing it to a total of approximately six minutes for each participant.

At the end of the experiment, participants were asked to fill the Godspeed questionnaire aimed at capturing their impression of the virtual human. The participants were also interviewed informally to capture possible findings not targeted by the questionnaire or the general experimental procedure.

Figure 20 Participant during Study3

6.3.9 Method of Data Analysis

Please see Chapter 4, Section 4.3.9.

6.4 Results and Discussion

6.4.1 Introduction

To avoid excessive repetition, we have adopted a naming convention for our experimental conditions. Due to the counterbalancing of conditions adopted in this study, the suffixes 1 and 2 for conditions adopted in our previous two studies are not applicable here. Therefore, we shall refer to the conditions as “friendly-condition” when the virtual human confederate takes a friendly role and “unfriendly-condition” when the virtual human confederate takes an unfriendly role. Meanwhile, participants were not considered along the lines of gamers and non-gamers because as much as the split in the previous two studies suggested an effect emanating from this criterion, it was not consistent across the studies. Moreover, a brief interview of participants before the experiment suggested that none of the participants had experienced the immersive suite or a similar immersive projection.

The results of the Godspeed questionnaire (Likeability section) is presented first. This result establishes if participants like the virtual human confederate in the friendly-condition better than the virtual human confederate in the unfriendly-condition. fNIRS results are also presented.

6.4.2 Results

Godspeed Questionnaire (Likeability Section) data

All fourteen participants completed the experiment and filled out a standard Godspeed Questionnaire which captures measures on a 5-point Likert scale (Fig 21). The focus was on the Likeability section of the Questionnaire which measures five properties: Likeness, Friendliness, Kindness, Pleasantness and Niceness (Table 6).

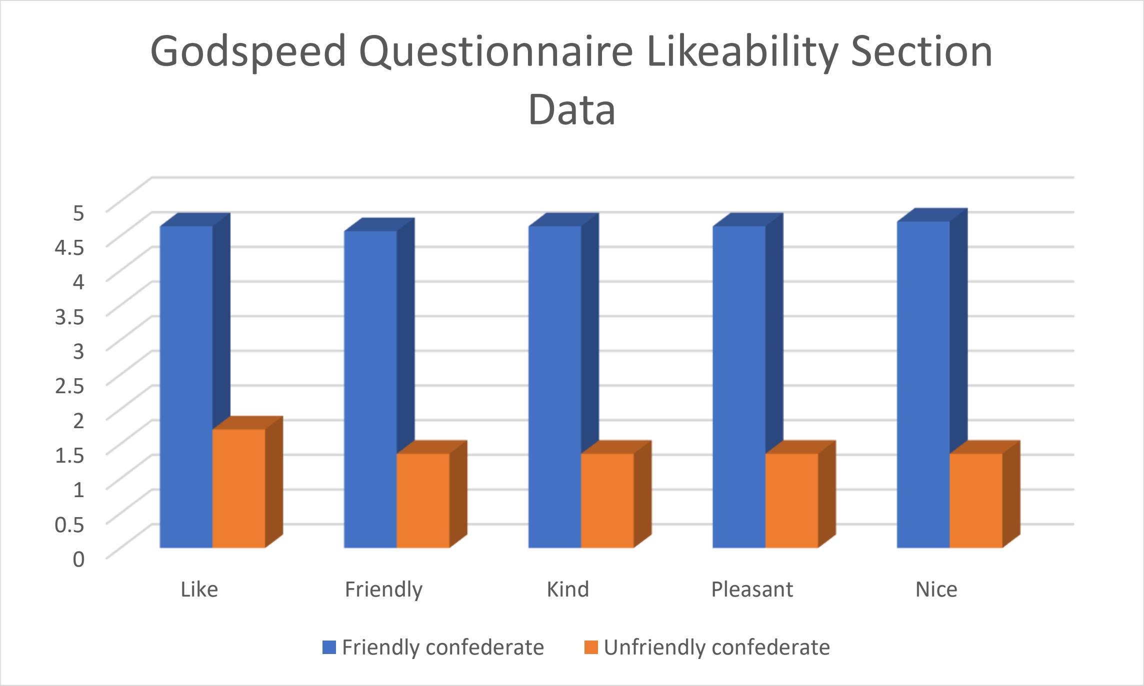


Figure 21 Descriptive Statistics for Godspeed questionnaire (Likeability section) data.

	Like	Friendly	Kind	Pleasant	Nice
Z	-3.332^b	-3.407^b	-3.355^b	-3.376^b	-3.360^b
Significance	.001	.001	.001	.001	.001

Table 6 Wilcoxon Signed Ranks Test Result for Godspeed questionnaire data.

Functional Near-Infrared Spectroscopy (fNIRS) data

Unlike our previous two studies, participants were not split along the lines of prior experience with VR and gaming, therefore, all N = 14 participants were included in this analysis. Meanwhile, the mistakes of the first two studies as regards bandpass filters and focus on null hypothesis was also avoided, therefore, the correct bandpass filters were used throughout this analysis and none of the hypothesis was based on a null hypothesis.

SPM level 1 analysis showed significant activation in both conditions compared to baseline for each of the (N = 14) participants.

SPM level 2 analysis also showed statistically significant activation, albeit in only the dorsolateral prefrontal cortex (DLPFC) (Figure 22)

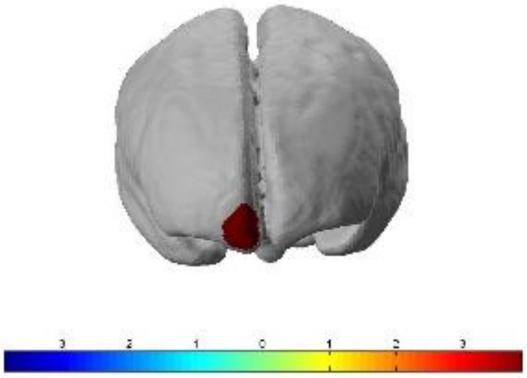


Figure 22 SPM Level2 data for Study3

Activation here refers to increased blood oxygenation within the dorsolateral prefrontal cortex during the conversation with the unfriendly virtual human confederate compared to that during the conversation with the friendly virtual confederate. Following our findings, we reject the null hypothesis for H2. However, we do not have enough evidence the reject the null hypothesis for H3.

6.4.3 Discussion

The hypotheses are listed in section 6.3.3.

Godspeed Questionnaire

Like the previous two studies, the Wilcoxon Signed Rank Test (WSRT) has been adopted in data analysis because the data is not normally distributed, and the same participants are repeated for both conditions.

The results show statistically significant evidence that participants liked the virtual human confederate in the friendly-condition better than the virtual confederate in the unfriendly-condition. This is in-line with previous studies which suggest that verbal aggressiveness triggers negative emotions (Infante & Wigley III, 1986).

The finding was associated with a strong statistically significant effect of approximately p = 0.001. Therefore, the null hypothesis for H1 is rejected. Rejecting the null hypothesis for H1 was key in this study as there would have been no basis for measuring the neural correlates of the emotions triggered by the virtual human confederate if the differences between participants' perception of the different roles of the virtual human confederate could not be established.

fNIRS data

We hypothesised that increased activity will be found in the dorsolateral prefrontal cortex (DLPFC) and medial prefrontal cortex (MPFC) when the virtual human assumes an unfriendly role (unfriendly-condition) compared to the friendly role (friendly-condition). The interest in these brain regions is discussed in the rationale behind the PhD. This interest is also influenced by the conflicts in opinion on the regions of the PFC implicated during inhibition. These regions have often been of interest to previous studies.

A statistically significant increase in activity was only shown in the DLPFC (H2), following this, we reject the null hypothesis for H2: "Participants will exhibit increased activation of the DLPFC while conversing with the unfriendly virtual human confederate". Several studies have associated the DLPFC with emotional regulation, reappraisal and rumination (Stramaccia et al., 2015; Joormann & Gotlib, 2010; MacDonald, Cohen, Stenger, & Carter, 2000; Ray et al., 2005; Rilling & Sanfey, 2009). The increased activity can be attributed to the fact that the unfriendly condition presented a higher need for emotional regulation and suppression (related to inhibition) as highlighted in previous studies. Our literature review suggested a similarity between emotional regulation during social interaction and inhibition, especially in the mechanism behind them (Bartholomew et al., 2019). Based on this, inhibitory control and emotional regulation are used similarly throughout this thesis. The results from this study is in line with the findings from our first study (Study1) involving participants with no prior experience with virtual reality (VR) and gaming, *non-gamers*. The similarities between these results can be linked to the fact that participants for the current study had no prior experience with an immersive suite just like the non-gamers had no prior experience with VR and gaming in Study1. Although this evidence may not be strong enough and requires a more thorough approach, we speculate that prior exposure to technology could potentially play a role in neural activity, especially around the DLPFC. This is not an area of interest in this research and is therefore not investigated further.

The implication of the DLPFC in this study agrees with Stramaccia et al (2015), earlier referenced in our rationale (section 3.5), which suggests that the DLPFC is largely responsible for inhibition. Although we admit that some other studies have also suggested the MPFC is involved in inhibition, we failed to find statistical evidence to support this within this study. Our findings are in line with the body of evidence that has implicated the DLPFC for inhibition and related regulations which share similar neural mechanisms with inhibition (Goldin, McRae, Ramel, & Gross, 2008; Bartholomew et al., 2019).

Meanwhile, this study failed to show a statistically significant increase in activity around the MPFC, although the MPFC has been linked with inhibition in the past (Narayanan et al., 2017). Apart from inhibition, the MPFC is also regarded as part of the human social brain (Grossmann, 2019), a significant change in MPFC activity may suggest a higher level of social involvement in one condition compared to the other. We cannot draw any conclusion on this as this finding differs from some of the previous findings of our studies; moreover, the social brain as defined by Grossman (2019) also includes other parts of the larger brain outside the PFC. At this stage of understanding, we can only speculate that MPFC involvement in the friendly-condition and unfriendly-condition remained either unchanged or minimally affected across participants. Again, this is similar to the findings for *gamers* in Study1. Although this study focuses on the PFC, we know that a network of the larger brain is also implicated in most executive functions; therefore, it is difficult to explain this outcome with the available information. This study depends totally on the outcome of the experiment with a focus on the PFC; following this, we reject the alternate hypothesis to H3: “Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) while conversing with the friendly virtual human confederate”.

6.5 Conclusion

In summary, participants perception of the virtual human confederate showed that they found the virtual human friendlier when the confederate assumed a friendly role (friendly condition). This was measured using the likeability section of the Godspeed Questionnaire. We, therefore, reject the null hypothesis for H1. Rejecting the null hypothesis for H1 was necessary because the fNIRS experiments were designed on this assumption.

Since the same virtual human confederate was used for both conditions in this study, it is unlikely that any bias would have emanated from participants' perception of the virtual human. Therefore, we argue that any significant effect observed in the experiment would have resulted from the verbal and non-verbal cues displayed by the virtual human confederate in the course of the conversation. Meanwhile, experimental conditions were counterbalanced in this study. This was aimed at eliminating possible arguments linking the results to the order of the experimental conditions.

Our findings showed a statistically significant increase in dorsolateral prefrontal cortex (DLPFC) activity, hence we reject the null hypothesis for H2. Previous studies have severally linked the DLPFC with activities such as regulation, reappraisal and rumination (Rilling & Sanfey, 2009). From the standpoint of Diamond (2013), these activities are indicative of inhibition. Following this and the rejection of the null hypothesis for H2, we argue that the virtual human confederate is capable of evoking neural responses indicative of inhibition in humans. However, it is important to note that the extent to which the DLPFC alone accounts for inhibition remains unclear.

Our results failed to show statistically significant evidence of activity in the medial prefrontal cortex (MPFC). Therefore, we fail to reject the null hypothesis for H3.

CHAPTER 7

DISCUSSION

7.1 What was done

Three studies were carried out to investigate if virtual humans can trigger measurable neural response indicative of inhibition during conversation. The first study adopted a virtual reality head-mounted display (the oculus rift DK2), the second study adopted a large 50-inch display screen while the third study adopted the immersive suite at Mary Seacole Building of the University of Salford. The research set out to use the VR head-mounted display (HMD) initially, but challenges encountered with this device informed subsequent studies using different (less cumbersome) devices. Although the goals varied with studies, each of the studies retained the primary aim of the research.

All three studies adopted the functional near infrared spectroscopy (fNIRS) device for neuroimaging and the Godspeed questionnaire series for measuring participants' perception of virtual humans.

We briefly discuss what was done in each study. We have represented the studies as Study1, Study2 and Study3 respectively.

7.2 Study 1

At the start of the PhD, we set out to run a study with healthy participants and a second study targeting participants that have been diagnosed with anti-social behaviour. The oculus rift DK2 was the proposed display system for these two studies. This study was the first of the two studies planned. The aim of was the same as the primary aim of the PhD: To investigate if virtual humans can trigger measurable neural responses indicative of inhibition in humans during a conversation. The study was carried out using the oculus rift DK2 as proposed, however, data analysis and activities during the study suggested the non-suitability of this display system for this study. As a result of this, subsequent studies explored other display systems.

Details of this study are captured in chapter 4.

7.3 Study 2

We encountered a high data exclusion rate during the initial analysis of Study1 albeit with wrong low bandpass filters. This study was aimed at investigating if virtual humans are capable of triggering neural responses indicative of inhibition using a different display system, this time a 50-inch display screen. This study provides a level of validation to the outcome of valid data from Study1 by comparing the outcome of Study1, which used virtual reality (VR) head-mounted display (HMD) with its outcome. No changes were made to the design of the system used in Study 1.

Details of this study are captured in chapter 5.

7.4 Study 3

This study also shared the primary aim of the research; however, it adopted the immersive suite located at the Mary Seacole building of the University. This study employed increased rigour both in procedure and quality of virtual human confederate.

Details of this study are captured in chapter 6.

The research questions these studies sought to answer are:

Are virtual humans capable of triggering measurable prefrontal cortex (PFC) responses in humans during social interaction?

Are these neural responses indicative of inhibitions?

What kind of display system better suits this kind of study?

The first two are the primary research questions while the third is the secondary question which came up in the course of the PhD. The extent to which the questions are answered in the course of this research is discussed in the rest of the chapter.

7.5 Results Summary

7.5.1 Godspeed Questionnaire

This was analysed using a Wilcoxon’s signed ranks test

(Table 7 shows records for all three studies and p-values)

	Like	**Friendly**	**Kind**	**Pleasant**	**Nice**
Study1	0.000	0.000	0.000	0.000	0.000
Study2	0.0042	0.0039	0.0036	0.0035	0.0036
Study3	0.001	0.001	0.001	0.001	0.001

Table 7 p-values for Godspeed questionnaire series likeability section comparison between the friendly and unfriendly virtual human confederates

Table 7 demonstrates that all three studies showed statistically significant evidence that participants liked the friendly virtual human better. However, the level of significance varied across the studies. Study1 showed the strongest statistical evidence of the three studies, while Study2 showed the weakest. This is proportional to the level of immersion inherent in the display systems.

Although this was not the aim of the research, our findings suggest a relationship between immersion and perception of virtual objects. This outcome is in line with previous studies (Loomis, Blascovich, Beall, & computers, 1999; Steinicke et al., 2009). Meanwhile, as mentioned in previous chapters, establishing statistically significant evidence of friendliness was key to proceeding with the rest of the experiment in all three cases. Since this criterion was met with all experiments, we argue that the virtual human confederates adopted in these studies showed sufficient cues (verbal/non-verbal) to create the impression of friendliness or unfriendliness. We have not isolated verbal and non-verbal communication because this was not the focus of this research. Therefore, we are unable to tell the extent to which either of them contributed to this perception of friendliness or otherwise of the virtual human confederates. We, however, argue that in isolation, these cues do not make naturalistic conversations.

7.5.2 fNIRS data

Statistical Parametric Mapping was adopted in the analysis of fNIRS data. The result summary within our regions of interest is shown in the table below. The first table shows the outcome of Study1 and Study2, while the second shows the outcome of Study3. We have separated the tables because we had considered prior experience with gaming with the first two studies, but this was not considered in the third study. We decided not to consider prior gaming experience in the third study because the results from the first two studies based on this criterion were not consistent. Moreover, initial conversation with participants before the experiment also suggests that the immersive suite adopted in the third study had not been experienced by any of our participants before the study. However, it will be interesting investigating the effect of prior experience with technology on learning outcomes of a similar experiment in the future.

Within the tables, we have used “+ve” in cases where there was significantly increased activity in the Region of Interest (ROI) during the conversation with the unfriendly virtual human confederate, “-ve” in cases where we observed a significant decrease in activity within the ROI during a conversation with the unfriendly virtual human confederate and “0” where we observed no significant change in activity within the ROI between the two conditions. We note that “-ve” activity here implies that there was a significant increase in activation in the ROI during the conversation with the friendly virtual human confederate.

	Gamers		**Non-Gamers**		
	DLPFC	**MPFC**	**DLPFC**	**MPFC**	**Comment**
Study1	0	-ve	+ve	0	Reject null hypothesis for DLPFC for Non-Gamers
Study2	-ve	-ve	0	-ve	Insufficient evidence to reject the null hypothesis for any region and group.

Table 8 Table showing ROI activation for Study1 and Study2

	DLPFC	**MPFC**	**Comment**
Study3	+ve	0	We reject the null hypothesis for DLPFC

Table 9 Table showing ROI activation for Study3

Initial data analysis was aimed at all the participants, but SPM Level2 analysis failed to find any significant activation in our regions of interest in Study1 and Study2. This changed however when the data were analysed along the lines of prior experience with Virtual Reality (VR) and gaming (Table 8). This has been briefly highlighted above. We refer to the group with prior experience with VR and gaming as **gamers**, and the group with no prior experience as **non-gamers**. In Study1, the gamers showed an unusual decreased activation in the medial prefrontal cortex (MPFC) during the conversation with the unfriendly virtual human confederate. Whilst this was not the expected outcome of this study, this outcome suggests that this group of participants in line with the Theory of Inhibition (Houdé & Borst, 2015) may have remained in a latent state of attention longer in the friendly condition than the unfriendly one. Latent state of attention here according to the Theory of inhibition refers to a state where the neural correlates of attention are not yet developed for neural activity. The MPFC has also been identified as part of the social brain (Blakemore, 2008), therefore, we are tempted to argue that this class of participants were more socially engaged with the friendly virtual human confederate. This argument, like every other neural basis argument presented in this study, is however limited to findings within the prefrontal cortex; the larger parts of the brain region referred to as the social brain is outside the PFC. Meanwhile, one can also link this outcome to the Theory of mind (Mahy et al., 2014) in this case, the friendly nature of the conversation could have allowed the participants sufficient time and opportunity to attribute mental states to themselves and the friendly virtual human confederate. The unfriendly virtual human confederate failed to show the ability to attribute mental states to the emotional states of participants as required by the theory of mind, which is important in face to face conversations. This could have contributed to the decrease in MPFC activity during the conversation with the unfriendly virtual human confederate. We acknowledge however that this argument may not be strong enough to be presented as a key finding in this research as the outcome was not consistent across all the studies.

On the other hand, the non-gamers showed significantly increased activity in the dorsolateral prefrontal cortex (DLPFC) during the conversation with the unfriendly virtual human confederate as expected. Details have been provided in Chapter 4.

Study 2 results failed to show statistical evidence to reject the null hypothesis for our PFC measures. Instead, we observed decrease activity in the MPFC and DLPFC for gamers and decrease MPFC activity for non-gamers. Just like with Study1, these findings suggest a generally higher PFC activation during the first condition (conversation with friendly confederate). Comparison between Study1 and Study2 using the individual outcomes of the studies using fNIRS showed no similarities between the PFC region implicated in each condition. fNIRS data were also captured during the Hayling sentence completion task. A paired sample t-test on the results showed no statistically significant difference between the two outcomes. We note that the low number of participants (split along the lines of gamers and non-gamers) may have adversely influenced the outcome of this study. Considering all N=10 participants for this study together failed to show any statistically significant difference ($p<0.05$) between the two conditions.

For Study3, information on participants' prior experience to VR and gaming was not captured (Table 8). This was because Study2 failed to show the impact of prior experience with VR and gaming on participants' performance. This outcome may be related to the number of participants (N=10), which was significantly reduced when participants were split along the lines of gamers and non-gamers. However, there were no indications of similar findings in PFC activation in the two previous studies when split along the lines of gamers and non-gamers. Meanwhile, information on participants' prior exposure to systems like the immersive suite was gathered, albeit informally. None of the (N=14) participants had prior experience with this or similar technology. As a result of these, SPM Level2 analysis for Study3 targeted all participants together without a focus on prior experience to VR and gaming. The experimental rigour was also improved and counterbalancing of conditions was introduced in Study3. This study showed a statistically significant increase in the DLPFC during the conversation with the unfriendly virtual human confederate. This outcome is consistent with that observed with non-gamers in Study1. It also ties well with several studies on emotional regulation where the DLPFC has been implicated.

Although our studies were not focused on the impact of prior experience to gaming on our participants, we argue that prior experience with equipment may significantly impact on the outcome of the studies as observed in Study1. In addition to the outcome of Study1, similarity exists between the outcome of our (N=14) participants in Study3 who had no prior experience with the immersive suite, and the outcome with non-gamers in Study1. Therefore, investigating the impact of prior experience with technology on cognition may be of interest in the future.

7.5.3 Hypothesis Testing

Here we list all the hypothesis for each of the studies. Although the first three hypotheses are the same for all three studies, we repeat them under each of the studies for clarity.

Study1

H1: Godspeed questionnaire data will show participants like the friendly virtual confederate better

H2: Participants will exhibit an increase in activation of the dorsolateral prefrontal cortex (DLPFC) during the conversation with the unfriendly virtual human confederate.

H3: Participants will exhibit an increase in activation of the medial prefrontal cortex (MPFC) during the conversation with the unfriendly virtual human confederate.

Study2

H1: Same as H1 for Study1

H2: Same as Study1

H3: Same as Study1.

H4: fNIRS data for Study1 and Study2 will show no significant difference in Region of Interest (ROI) activation form conversational task.

H5: fNIRS data for Hayling task and the conversational task will show no significant difference in ROI activation

Study3

H1: Same as Study1

H2: Same as Study1.

H3: Same as Study1.

A Wilcoxon's signed rank test of the likeability section of the Godspeed questionnaire for each study showed that participants liked the friendly virtual human confederate better than the unfriendly one in all three studies. We, therefore, reject the null hypothesis for H1 for all three studies. Rejecting the null hypothesis for H1 was a basis for proceeding with the fNIRS data analysis.

SPM level 2 analysis of all combined fNIRS data for Study1 and Study2 failed to show any significant increase in activation within the DLPFC and MPFC; therefore, we fail to reject the null hypothesis for H2 and H3.

However, a pattern was observed during data analysis which was peculiar to participants with no prior experience with VR and gaming. Information on participants' experience with VR and gaming was gathered informally before the experiment. Using this information, participants' data were split into two groups: Gamers [(N=7) for Study1 and (N=6) for Study2] representing participants with prior experience with VR and gaming and Non-Gamers [(N=12) for Study1 and (N=4) for Study2] representing those without prior experience with VR and gaming as described in Section 7.2 above. This only applies to Study1 and Study2.

Subsequent analysis along the lines of Gamers and Non-Gamers was unable to show enough evidence to reject the null hypothesis for H2 and H3 for Gamers in both studies. However, we observed a statistically significant decrease within the MPFC when the conversation moved to the unfriendly virtual human confederate in Study1; this decrease extended to the DLPFC in Study2. Most of these are already highlighted in Section 7.3 above.

Non-Gamers, on the other hand, showed a statistically significant increase within the DLPFC during the conversation with the unfriendly virtual human in Study1. We, therefore, reject the null hypothesis for H2 for this study. There was no statistically significant change in MPFC activity for Non-Gamers, therefore we fail to reject the null hypothesis for H3 for Study1.

Non-Gamers in Study2 showed a statistically significant decrease in effect within the MPFC when conversing with the unfriendly virtual human confederate and no significant change in activity in the DLPFC. We, therefore, fail to reject the null hypothesis for H2 and H3.

Meanwhile, we conducted a region of interest analysis on Study1 and Study2 data based on the BA atlas (Brodmann, 1909). A t-test analysis was run on these ROIs separately and subsequently a MANOVA on data from both studies, no significant difference was found between these outcomes. Following this, we reject the null hypothesis for H4. Furthermore, observatory comparison of both studies following SPM Level2 analysis also shows similarities between the studies.

Moreover, in Study2, we attempted capturing the neural basis of the Hayling sentence completion task. The Hayling task showed no statistically significant change in any of the ROIs, comparing the outcome of the Hayling task to the conversational task showed no statistically significant difference between the two outcomes. We, therefore, reject the null hypothesis for H5.

Study3 did not utilise information on prior experience to VR and gaming as reported in the previous two studies. This information was not utilised because the outcome of categorising participants' data based on prior experience with VR and gaming was not consistent across the first two studies. Moreover, none of these (N=14) participants affirmed to having experienced a technology similar to the immersive suite. All available data for (N=14) participants was analysed together. SPM Level2 analysis showed a statistically significant increase in activity within the DLPFC during the conversation with the unfriendly virtual human confederate. No significant change in activity was reported in the MPFC, we, therefore, reject the null hypothesis for H2. This finding ties well with studies that have attempted to implicate the DLPFC during emotional regulatory tasks and reappraisal (Gillespie & Beech, 2016) as well as studies that have reported the implication of the DLPFC during inhibition (Houdé & Borst, 2015). In line with the neural basis of the theoretical frameworks on which this research was developed (section 3.4), the DLPFC is implicated in all three frameworks except the Theory of mind in which only the MPFC is implicated in our two regions of interest (Gallagher & Frith, 2003). This outcome does not suggest a non-implication of the MPFC in the experiment; it only suggests that there was no significant change resulting from the unfriendliness of the virtual human confederate as recorded within the MPFC. The implication of the DLPFC in our study suggests a similarity between our findings, the theory of inhibition and the theory of emotional regulation (Houdé & Borst, 2015; Etkin, Büchel, & Gross, 2015). Our literature review also suggests a similarity between inhibition and emotional regulation, and the mechanism behind them (Bartholomew et al., 2019), and following this, they were used interchangeably throughout the thesis.

Meanwhile, our findings also suggest similarities between face-to-face interaction and interaction represented by the implied presence of the virtual human confederate as adopted by Schilbach (2006). Although the experimental tasks were different in these studies, the DLPFC was implicated in both. Whilst this study may not be strong enough to draw conclusions that underscore the need for face-to-face conversation, further investigation focusing primarily on this may suggest the sufficiency of the implied presence of our virtual human confederates as defined by Allport (1985). However, behavioural realism (Blascovich et al, 2002) remains a key consideration in making this decision.

7.5.4 Limitation of Study

The neuro-imaging aspect of this study has been carried out using the fNIRS which is only able to investigate a change in haemoglobin concentration within the frontal lobe which consists of the prefrontal cortex (PFC) (Fuster, 2000; E. E. Smith & Jonides, 1999). Inhibition is reported as one of the core executive functions (Locascio, Mahone, Eason, & Cutting, 2010; Shields, Bonner, & Moons, 2015) and the prefrontal cortex is PFC plays an essential role in this process (Denckla, 1996; Koechlin & Summerfield, 2007). Therefore, the findings from this study are limited to neural activity as indicated in the PFC due to the limitations of the fNIRS.

Meanwhile, previous studies suggest that the MPFC is part of the social brain (Blakemore, 2008). Although this may not adequately account for the interaction side of things, we believe that the MPFC can reasonably suggest pointers to infer the social brain activity during conversations. A neuro-imaging tool suited to measuring deeper brain regions, such as the fMRI could have provided stronger evidence within the social brain, however naturalistic movement of participants may not be feasible with this tool. Also, the fMRI is not suitable for real-time capture of brain data, hence the choice of the fNIRS for this research.

In a bid to create a platform that allowed for naturalistic conversations, the tasks have not been broken into blocks of activity, therefore data were analysed by supplying varying time lengths (t) for each condition in NIRSLAB (one of the tools for analysing fNIRS data). This, in turn, impacted our choice of low band-pass filter which was calculated by finding the reciprocal of longer t of the two conditions. Breaking conversations into blocks of time-slots would have allowed for more conventional neuro-imaging approaches with the same low band-pass filter and this could have impacted directly on our outcome. However, we argue that breaking conversations into these blocks would have defeated the purpose of this research.

Meanwhile, due to ethical considerations, all findings are limited to healthy participants. Healthy here refers to participants with no previous diagnosis of mental illness. No attention was paid to demographic information of participants. As this was not the focus of this research currently.

Responses of virtual humans have been pre-recorded and are controlled using the wizard of Oz (WoZ) approach (button presses on keyboards). This approach brings the advantage of controllability as opposed to natural language processing (NLP) and other artificial intelligence (AI) approaches. NLPs can get out of hand and defeat the purpose of this research (Bates & Weischedel, 2006; Chowdhury & technology, 2003). However, the WoZ approach requires the presence of an operator at every point in time to make decisions on what buttons to press. We argue that this approach is enough for this research and the approach is suitable for both immersive virtual reality display systems as well as non-immersive displays especially ones with wireless keyboards.

The cues displayed by the virtual humans used in our studies are limited to cues that can be exhibited while sitting. Movement of virtual humans may have offered more naturalistic conversation scenarios with increased non-verbal cues, nonetheless, the cues exhibited by the virtual humans were sufficient to establish a difference in likeability as measured by the Godspeed questionnaire. Meanwhile, movement of our virtual confederates could have implied allowing for movement of our participants which may increase the possibility of encountering noisy data due to movement (Landowska, Royle, Eachus, & Roberts, 2018).

7.6 Critical Analysis

The prefrontal cortex (PFC) has been linked with several executive functions, from inhibition to emotional regulation and working memory. Whilst some of these executive functions are well distinguished, others are quite similar and often used interchangeably.

This research was aimed at triggering and measuring neural responses indicative of inhibition; however, inhibition falls into the category of executive functions that are similar to other executive functions. Paradigms exist that attempt to evaluate inhibition, one of these paradigms is the Hayling sentence completion task. Following the success of the Hayling sentence completion task and its ease of implementation, we adopted this task intending to compare the expected outcome to the uncertain outcome of our experimental task. We expected to find a pattern between both outcomes; however, the sample strength required to achieve this pattern matching through correlation may not have been met during the first two studies. Consequently, we excluded this task from the third study. However, there is no gainsaying that a positive correlation between the experimental task and the Hayling sentence completion task would have strengthened the outcome of this research. Our arguments will potentially benefit from further studies specifically targeting neuroimaging and the paradigms for assessing executive functions.

Meanwhile, our literature review suggests an overlap between emotional regulation and inhibition especially within the social domain (Sani, Tabibi, Fadardi, & Stavrinos, 2017; Serrano-Ibanez et al., 2018). While we are tempted to make assumptions in agreement with previous studies suggesting that these concepts share similar underlying mechanisms (Bartholomew et al., 2019) and, have been used interchangeably in several studies including some sections of this thesis, this assumption will benefit from a study that attempts to separate these concepts within the social domain. This potential study can also be extended to cover executive functions such as working memory. This is necessary as the PFC has been associated with these executive functions and establishing that each of these functions can be sufficiently separated from each other validates similar future studies that may be interested in inhibition only.

This research adopted VR and virtual humans as tools to trigger neural responses, however, one can argue against the suitability of VR for research of this nature especially with the anti-social behaviour component. Whilst this argument is valid, it is also worthy to note that obtaining ethical approval to use real human confederates may be difficult. Meanwhile, although a more comprehensive body of research is needed to fully map the overlap between real life and VR, there is growing evidence suggesting behavioural similarities between how people react in real life and VR; in line with this evidence and the studies in this research, we argue that VR is indeed suitable for this research. However, using trained real human confederates brings several advantages which include ease of implementation and more naturalistic cues (verbal and non-verbal). Although it also introduces disadvantages such as fatigue of confederates and difficulty of repeatability of the experiment, our study will benefit from future studies attempting to repeat these experiments using real human confederates (this will be dependent on the possibility of obtaining ethical approval for such a study).

7.7 Future work

The PhD has focused on an area of research that has not been widely explored and the findings also open doors to possible new areas of research for future works. This research and its studies find potential significance with therapies targeting mental health deficits. An example of such therapies is the treatment of PTSD where a therapist intends to make a patient re-live a lifethreatening traumatic experience. Immersive technology can be used to recreate these experiences in VR while neural correlates can be measured and analysed over a period.

Following an initial partnership with Pennine Care NHS Foundation, Dr Alan Barrett who is a Consultant Clinical Psychologist at Pennine saw potential in this work. Dr Alan Barrett and his team suggested a potential application of this system in therapies and treatments for anti-social behaviour, which is common in mental health deficits such as PTSD. Future modifications of this project will target clinical aspects which will potentially be driven by affiliated clinicians.

Following our studies, other potentially interesting dimensions to this research in the future may include:

Fitting conversations into blocks of equal time frames to investigate neural activities using a more conventional approach and comparing findings to our findings. This is the first research that has attempted to investigate neural activity during an active conversation. In carrying out these set of experiments, we have attempted to keep the conversation as naturalistic as possible, therefore there was no need introducing time constraints to the conversation as this may introduce another variable to the task. However, the unconstrained timings for each of the conditions affected the data analysis and as a result of this, we improvised on the fNIRS data analysis because the conditions were not in equally time blocks. Future works may find interest in fitting these conversations into blocks of equal time slots. The variables and hypothesis for this potential study do not have to differ from those of this research.

Attempting to quantify prior experience with VR and gaming and correlating with neural response. In the course of this study, we learnt that prior experience with VR and gaming may potentially affect performance with VR experiments, however, this did not seem consistent across the first two experiments. As the number of subjects was too modest to test this, a larger study is needed. It might be pertinent to group subjects according to the type of experience, e.g. VR, virtual humans, gaming and to use a scale to rate the level of experience.

Introducing some form of eye-tracking may improve qualitative measures in future studies. More advanced gaze modelling may also improve user experience. A combination of these may help with improving non-verbal communication. A likely issue with this, however, is the cumbersomeness that may emanate from combining the fNIRS and eye-tracking devices. The advantages of eye-tracking potentially outweigh the disadvantages in that more responsive virtual human confederates can be created if this feature is available. Non-verbal gestures and body languages can be configured for the virtual human confederates to change as the tracked gaze changes. Actions can be configured for mutual gaze scenarios between the participants and virtual humans, and gaze avoidance can also be detected from the participants. The variables and hypothesis for this potential study could remain the same with the research.

Extending this research to participants with mild cognitive impairments. This was planned at the start of the PhD, however, a change in direction became necessary after the first study and comments from examiners. This is still at the core of the application of this research and will be pursued in future endeavours.

Attempting to modify the design of the virtual human confederates to adopt Artificial Intelligence (AI) rather than of the Wizard of oz (Woz) approach. A possible attempt can target components such as improvisational behaviour, natural language processing (NLP) and predictable cognitive models. Improvisational behaviour refers to behaviour which is determined by patterns in communication flow and not by single keypresses or decision of an operator.

Mobile phone app solution. VR solutions are increasingly gaining acceptability in the mobile apps market. Since the mobility of the systems was one of the considerations of this system at the start of the research, a mobile app will ultimately meet this requirement. With mobile apps, however, there will be a need to make decisions around how best to handle features such as button presses.

Testing in a clinical setting with real therapists and clients. This is fully achievable with all the setups except the HMD. The HMD brings the advantage of mobility and immersivity, however, combining this with the fNIRS makes it cumbersome and less likely to provide accurate results. the large screen display allows for the wearing of the fNIRS with less discomfort, and for having more than one participant with a therapist. However, it is less immersive and may not be suitable for this purpose. The immersive suite brings the advantage of allowing as many participants as required in the experiment to share the same immersive space.

Finally, the FNIRS currently ships with Application Programming Interfaces (APIs) that can be integrated into a real-time data capture process by the fNIRS. This feature could find useful application in creating dynamic tasks that target different PFC regions. Future works aimed at dynamic data capture and task management will find this feature potentially useful.

Implementing this feature may be highly time-consuming and require expertise with programming languages such as Java.

7.8 Conclusion

In this thesis, we attempted to address the question of virtual humans being able to trigger a prefrontal cortex response indicative of inhibiting an anti-social response in humans as they converse with virtual humans.

Although each of the studies showed a significant increase in different PFC regions as discussed earlier, in summary, we found a significant increase in activity in the dorsolateral prefrontal cortex (DLPFC) during the conversation with the unfriendly virtual human confederate. This finding was consistent across two studies (Study1 and Study3). The contribution here was adding to the existing body of knowledge (Reinecke et al., 2014; Schulze et al., 2011; Staudinger, Erk, & Walter, 2011) that have associated the DLPFC with reappraisal and emotional regulation. Meanwhile, we also learnt that inhibition within the social domain (social inhibition) is accounted for similarly to inhibition as investigated previously by paradigms such as the Stroop and Hayling tasks within the PFC.

We observed that the display medium contributed to participants perception of the virtual human confederates. The more immersive the display, the stronger participants impression of like/dislike. The impact of display systems has been explored previously (Lantz, 1997; Sharples, Cobb, Moody, & Wilson, 2008), hence another contribution to knowledge of this study lies within this comparison.

Furthermore, this PhD identified prior experience to VR and gaming as a component that can impact neural response to social interaction. This contributes to the vaguely explored (Granic, Lobel, & Engels, 2014) area of gaming and cognition.

This research has also contributed methodologically by developing a system/tool for investigating social interaction with virtual humans, especially the neural correlates of these interactions.

Ultimately, we have demonstrated that the fNIRS can be combined with immersive (head-mounted and projector based) and non-immersive displays. The difficulty of data capture with a head-mounted display (HMD), however, suggested validation of its outcome with non-head mounted displays. The outcome of our final study (immersive suite) ties well with the outcome with the head-mounted display albeit for a class of participants who have had little or no experience with VR and gaming previously; therefore, the advantage of mobility with HMDs is preserved.

In summary, as of today, of all our tested display systems, HMDs are the least suitable to capture neural data. Meanwhile, the level of immersion is proportional to the level of perception about virtual, therefore the use of projection technologies (such as the immersive suite) is more viable for these kinds of studies.

This is an emerging area of interest and in the course of this research, we have come across an increasing number of mental-health professionals who have shown interest in the study, most significant of these is Alan Barrett of Pennine Care Foundation. This suggests the likelihood of a surge in this area within the next few years. Although this PhD set out to understand the neural basis of social interaction in healthy participants, the PhD presented an opportunity to meet with clinicians who found this research potentially useful in therapies that target subjects with anti-social behaviour. This is common with people who have suffered PTSD. Since the researcher is neither a therapist nor a clinician, the information on its usefulness with this class of people was gathered from clinicians who were involved in several demonstrations of the VR system. Our findings will also potentially find a useful application in studies focusing on mental health.

Although this research finds potential usefulness on therapies associated with anti-social behaviour, one of the major interests for the researcher is the takeaway in terms of learning. In this course of the series of studies that have made up this research, we have learnt that whilst allowing naturalistic conversation may be important especially for mundane realism, the adequate arrangement has to be made in terms of neuroimaging and its associated data analysis. Since a common method with neuroimaging tools is to split experimental conditions into equal blocks of fixed seconds, naturalistic conversations may not follow this pattern, and this defeats the whole purpose of studies like this. We expect additional work to follow these studies to actualise the potentials earlier mentioned, and these key learnings, especially from the neuro-imaging perspective, will be applied.

In the course of this research, we also identified the extendibility of the fNIRS software to capture real-time data. Although this requires increased technical effort to achieve, the potential usefulness of this feature cannot be overestimated. An area of interest subsequently for the researcher would be to create virtual humans that generate stimuli based on feedback from realtime neuroimaging. Meanwhile, subsequent endeavours in this area will attempt to clearly distinguish between neurological evidence and behavioural evidence of inhibition. This research focused majorly on neuroimaging evidence because of the lack of consensus on behavioural evidence associated with inhibition within the social scene in the literatures. In the course of the studies, we tried monitoring behavioural pattern amongst our participants which were indicative of inhibition. We noticed some form of laughter a common behaviour across most participants during the unfriendly conversation (where we predicted increased inhibitory control). Although we believe this may not be a strong enough evidence, subsequent studies will look out for this behaviour amongst others.

Following what has been learnt from this research, we intend to build in these while exploring the potential of partnering with relevant professional especially clinicians, to create a system that meets clinical standards to actualise the potentials identified in the course of this research.

REFERENCES

Adolphs, R. (2009). The social brain: neural basis of social knowledge. *Annual review of psychology, 60*, 693-716.

Albright, G., Adam, C., Serri, D., Bleeker, S., & Goldman, R. (2016). Harnessing the power of conversations with virtual humans to change health behaviors. *Mhealth, 2*.

Allport, G. (1985). Psychology: The Briefer Course.

Aloia, L. S., & Solomon, D. H. (2016). Emotions associated with verbal aggression expression and suppression. *Western Journal of Communication, 80*(1), 3-20.

Amodio, D. M., & Frith, C. D. (2006). Meeting of minds: the medial frontal cortex and social cognition. *Nature reviews neuroscience, 7*(4), 268-277.

Anwar, A. R., Muthalib, M., Perrey, S., Galka, A., Granert, O., Wolff, S., ... & Muthuraman, M. (2016). Effective connectivity of cortical sensorimotor networks during finger movement tasks: a simultaneous fNIRS, fMRI, EEG study. *Brain topography, 29*(5), 645-660.

Argyle, M. (1972). Non-verbal communication in human social interaction. In R. A. Hinde, *Non-verbal communication.* Oxford, England: Cambridge U. Press.

Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *The neuroscientist, 13*(3), 214-228.

Ashton, N. L., Shaw, M. E., & Worsham, A. P. (1980). Affective reactions to interpersonal distances by friends and strangers. *Bulletin of the Psychonomic Society, 15*(5), 306-308. . doi:10.3758/bf03334541

Baer, J., Schreck, M., Althoff, R. R., Rettew, D., Harder, V., Ayer, L., . . . Hudziak, J. J. (2015). Child temperament, maternal parenting behavior, and child social functioning. *Journal of child and family studies, 24*(4), 1152-1162.

Baglivio, M. T., Wolff, K. T., DeLisi, M., Vaughn, M. G., & Piquero, A. R. (2016). Effortful control, negative emotionality, and juvenile recidivism: an empirical test of DeLisi and Vaughn's temperament-based theory of antisocial behavior. *The Journal of Forensic Psychiatry & Psychology, 27*(3), 376-403.

Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2003). Interpersonal distance in immersive virtual environments. *Personality and Social Psychology Bulletin, 29*(7), 819-833.

Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2001). Equilibrium theory revisited: Mutual gaze and personal space in virtual environments. *Presence: Teleoperators & Virtual Environments, 10*(6), 583-598.

Bandura, A. (1978). Social learning theory of aggression. *Journal of communication, 28*(3), 12-29.

Bartneck, C., Croft, E., & Kulic, D. (2008). Measuring the anthropomorphism, animacy, likeability, perceived intelligence and perceived safety of robots. *Paper presented at the Metrics for HRI workshop, technical report*.

Bartneck, C., Kulić, D., Croft, E., & Zoghbi, S. (2009). Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. *International journal of social robotics, 1*(1), 71-81.

Bartholomew, M. E., Heller, W., & Miller, G. A. (2019). Inhibitory control of emotional processing: Theoretical and empirical considerations. *International Journal of Psychophysiology*.

Bassett, H. H., Denham, S. A., Fettig, N. B., Curby, T. W., Mohtasham, M., & Austin, N. (2016). Temperament in the classroom Children low in surgency are more sensitive to teachers' reactions to emotions. *International Journal of Behavioral Development,* 0165025416644077.

Bates, M., & Weischedel, R. M. (2006). *Challenges in natural language processing*: Cambridge University Press.

Baumgartner, T., Speck, D., Wettstein, D., Masnari, O., Beeli, G., & Jäncke, L. (2008). Feeling present in arousing virtual reality worlds: prefrontal brain regions differentially orchestrate presence experience in adults and children. *Frontiers in human neuroscience*, *2*, 8.

Baus, O., & Bouchard, S. (2014). Moving from virtual reality exposure-based therapy to augmented reality exposure-based therapy: a review. *Frontiers in human neuroscience*, *8*, 112.

Belanger, S., Belleville, S., & Gauthier, S. (2010). Inhibition impairments in Alzheimer's disease, mild cognitive impairment and healthy aging: effect of congruency proportion in a Stroop task. *Neuropsychologia*, *48*(2), 581-590. doi:10.1016/j.neuropsychologia.2009.10.021

Bera, A., Kim, S., & Manocha, D. (2016). *Interactive and adaptive data-driven crowd simulation: User study*. Paper presented at the 2016 IEEE Virtual Reality (VR).

Bielak, A. A., Mansueti, L., Strauss, E., & Dixon, R. A. (2006). Performance on the Hayling and Brixton tests in older adults: Norms and correlates. *Archives of Clinical Neuropsychology*, *21*(2), 141-149.

Blair, R. J. R. (2001). Neurocognitive models of aggression, the antisocial personality disorders, and psychopathy. *Journal of Neurology, Neurosurgery & Psychiatry*, *71*(6), 727-731.

Blakemore, S. J. (2008). The social brain in adolescence. *Nature Reviews Neuroscience*, *9*(4), 267-277.

Blascovich, J., Loomis, J., Beall, A. C., Swinth, K. R., Hoyt, C. L., & Bailenson, J. N. (2002). Immersive virtual environment technology as a methodological tool for social psychology. *Psychological inquiry*, *13*(2), 103-124.

Boehm, B. (1989, September). Software risk management. In *European Software Engineering Conference* (pp. 1-19). Springer, Berlin, Heidelberg.

Booth-Kewley, S., Larson, G. E., Highfill-McRoy, R. M., Garland, C. F., & Gaskin, T. A. (2010). Factors associated with antisocial behavior in combat veterans. *Aggressive behavior*, *36*(5), 330-337.

Botella, C., Villa, H., Baños, R., Perpiñá, C., & Garcia-Palacios, A. (1999). The treatment of claustrophobia with virtual reality: Changes in other phobic behaviors not specifically treated. *CyberPsychology & Behavior*, *2*(2), 135-141.

Brodmann, K. (1909). Comparative localization of the cerebral cortex presented in their principles due to cell construction. *Barth, Leipzig Google Scholar*.

Bruijnes, M., Linssen, J., op den Akker, R., Theune, M., Wapperom, S., Broekema, C., & Heylen, D. (2015). Social behaviour in police interviews: relating data to theories. In *Conflict and Multimodal Communication* (pp. 317-347): Springer.

Buck, R., Losow, J. I., Murphy, M. M., & Costanzo, P. (1992). Social facilitation and inhibition of emotional expression and communication. *Journal of Personality and Social Psychology*, 63(6), 962.

Buhle, J. T., Silvers, J. A., Wager, T. D., Lopez, R., Onyemekwu, C., Kober, H., ... & Ochsner, K. N. (2014). Cognitive reappraisal of emotion: a meta-analysis of human neuroimaging studies. *Cerebral cortex*, *24*(11), 2981-2990.

Burgess, P. W., & Shallice, T. (1996). Response suppression, initiation and strategy use following frontal lobe lesions. *Neuropsychologia*, *34*(4), 263-272. doi:https://doi.org/10.1016/0028-3932(95)00104-2

Burgess, P., & Shallice, T. (1997). The hayling and brixton tests. Test manual.

Burgoon, J. K., Guerrero, L. K., & Floyd, K. (2016). *Nonverbal communication*: Routledge.

Cali, C., Baghabra, J., Boges, D. J., Holst, G. R., Kreshuk, A., Hamprecht, F. A., . . . Magistretti, P. J. (2016). Three-dimensional immersive virtual reality for studying cellular compartments in 3D models from EM preparations of neural tissues. *Journal of Comparative Neurology, 524*(1), 23-38. doi:10.1002/cne.23852.

Campbell, Z., Zakzanis, K. K., Jovanovski, D., Joordens, S., Mraz, R., & Graham, S. J. (2009). Utilizing virtual reality to improve the ecological validity of clinical neuropsychology: an FMRI case study elucidating the neural basis of planning by comparing the Tower of London with a three-dimensional navigation task. *Applied Neuropsychology, 16*(4), 295-306.

Carlson, S. M., & Wang, T. S. (2007). Inhibitory control and emotion regulation in preschool children. *Cognitive Development, 22*(4), 489-510. doi:https://doi.org/10.1016/j.cogdev.2007.08.002

Carpenter, P. A., Just, M. A., & Reichle, E. D. (2000). Working memory and executive function: Evidence from neuroimaging. *Current opinion in neurobiology, 10*(2), 195-199.

Cassell, J., Sullivan, J., Churchill, E., & Prevost, S. (2000). *Embodied conversational agents*: MIT press.

Chelune, G. J., Ferguson, W., Koon, R., & Dickey, T. O. (1986). Frontal lobe disinhibition in attention deficit disorder. *Child Psychiatry and Human Development, 16*(4), 221-234.

Chowdhury, G. G. (2003). Natural language processing. *Annual review of information science and technology, 37*(1), 51-89.

Clark, C. J. (2016). Voice and Communication Therapy for the Transgender or Transsexual Client: Service Delivery and Treatment Options.

Cohen, J. (1992). A power primer. *Psychological bulletin, 112*(1), 155.

Collette, F., Van der Linden, M., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2001). The functional anatomy of inhibition processes investigated with the Hayling task. *Neuroimage, 14*(2), 258-267.

Collette, F., Hogge, M., Salmon, E., & Van der Linden, M. (2006). Exploration of the neural substrates of executive functioning by functional neuroimaging. *Neuroscience, 139*(1), 209-221.

Combs, H. L., Garcia-Willingham, N. E., Berry, D. T., van Horne, C. G., & Segerstrom, S. C. (2018). Psychological functioning in Parkinson's disease post-deep brain stimulation: Self-regulation and executive functioning. *Journal of psychosomatic research, 111*, 42-49. doi:10.1016/j.jpsychores.2018.05.007

Cook, T. B., Brenner, L. A., Cloninger, C. R., Langenberg, P., Igbide, A., Giegling, I., . . . Brundin, L. (2015). “Latent” infection with Toxoplasma gondii: Association with trait aggression and impulsivity in healthy adults. *Journal of psychiatric research, 60*, 87-94.

Cracco, E., Genschow, O., Radkova, I., & Brass, M. (2017). Automatic imitation of pro-and antisocial gestures: Is implicit social behavior censored? *Cognition, 170*, 179.

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

Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. *NeuroImage, 54*(4), 2808-2821. doi:10.1016/j.neuroimage.2010.10.069.

Dai, B., Chen, C., Long, Y., Zheng, L., Zhao, H., Bai, X., ... & Ding, G. (2018). Neural mechanisms for selectively tuning in to the target speaker in a naturalistic noisy situation. *Nature communications, 9*(1), 1-12.

Dahm, A. S., Schmierer, P., Veer, I. M., Streit, F., Görgen, A., Kruschwitz, J., ... & Erk, S. (2017). The burden of conscientiousness? Examining brain activation and cortisol response during social evaluative stress. *Psychoneuroendocrinology*, *78*, 48-56.

Dalton, C., Sciadas, R., & Nantel, J. (2016). Executive function is necessary for the regulation of the stepping activity when stepping in place in older adults. *Aging Clinical and Experimental Research, 28*(5), 909-915. doi:10.1007/s40520-015-0499-9

de Borst, A. W., & de Gelder, B. (2015). Is it the real deal? Perception of virtual characters versus humans: an affective cognitive neuroscience perspective. *Frontiers in Psychology*, *6*, 576. doi:10.3389/fpsyg.2015.00576

Deering, M. (1992). High resolution virtual reality. *SIGGRAPH Comput. Graph., 26*(2), 195-202. doi:10.1145/142920.134039

Deering, M. F. (1993, September). Data complexity for virtual reality: Where do all the triangles go?. In *Proceedings of IEEE Virtual Reality Annual International Symposium* (pp. 357-363). IEEE.

Denckla, M. B. (1996). A theory and model of executive function: A neuropsychological perspective.

Diamond, A. (2013). Executive functions. *Annual review of psychology*, *64,* 135-168.

deBeus, R. J., & Kaiser, D. A. (2011). Neurofeedback with children with attention deficit hyperactivity disorder: A randomized double-blind placebo-controlled study. In *Neurofeedback and neuromodulation techniques and applications* (pp. 127-152). Academic Press.

Denollet, J. (2013). Interpersonal sensitivity, social inhibition, and Type D personality: How and when are they associated with health? Comment on Marin and Miller (2013).

Dufner, M., Denissen, J., Sedikides, C., Van Zalk, M., Meeus, W. H., & Van Aken, M. (2013). Are actual and perceived intellectual self‐enhancers evaluated differently by social perceivers?. *European Journal of Personality,* 27(6), 621-633.

Dronkers, N., & Ogar, J. (2004). Brain areas involved in speech production.

Eme, R. (2016). Evolutionary roots of the sex difference in the prevalence of severe anti-social behavior: A litera-ture review. *Psychol Cogn Sci Open J*, *2*(2), 49-53.

Etkin, A., Büchel, C., & Gross, J. J. (2015). The neural bases of emotion regulation. *Nature Reviews Neuroscience, 16*, 693. doi:10.1038/nrn4044

Euston, D. R., Gruber, A. J., & McNaughton, B. L. (2012). The role of medial prefrontal cortex in memory and decision making. *Neuron*, *76*(6), 1057-1070.

Farrell, M. R., Holland, F. H., Shansky, R. M., & Brenhouse, H. C. (2016). Sex-specific effects of early life stress on social interaction and prefrontal cortex dendritic morphology in young rats. *Behavioural Brain Research, 310,* 119-125. doi:http://dx.doi.org/10.1016/j.bbr.2016.05.009

Fernandes, A. S., Wang, R. F., & Simons, D. J. (2015, September). Remembering the physical as virtual: source confusion and physical interaction in augmented reality. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception* (pp. 127-130).

Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *Neuroimage, 63*(2), 921-935.

Fonseca, L. M., Haddad, G. G., Mattar, G., de Oliveira, M. C., Guilhoto, L. M. D. F. F., Zaman, S., ... & de Campos Bottino, C. M. (2017). Dysexecutive Function, Disinhibition And Apathy And Their Correlation With Cognitive Decline And Alzheimer's Disease In Adults With Down Syndrome: Preliminary Results. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, *13*(7), P378-P379.

Freeman, D., Reeve, S., Robinson, A., Ehlers, A., Clark, D., Spanlang, B., & Slater, M. (2017). Virtual reality in the assessment, understanding, and treatment of mental health disorders. *Psychological Medicine*, 1-8.

Frith, C. D. (2007). The social brain? *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 362*(1480), 671-678.

Frith, C. D., & Frith, U. (2007). Social cognition in humans. *Current Biology*, *17*(16), R724-R732.

Fry, D. P., & Gabriel, A. H. (1994). Preface: The cultural construction of gender and aggression. *Sex Roles*, *30*(3-4), 165-167.

Fuster, J. M. (1973). Unit activity in prefrontal cortex during delayed-response performance: neuronal correlates of transient memory. *Journal of neurophysiology*, 36(1), 61-78.

Fuster, J. M. (2000). Memory networks in the prefrontal cortex. *Progress in brain research*, *122*, 309-316.

Gallagher, H. L., & Frith, C. D. (2003). Functional imaging of 'theory of mind'. *Trends in Cognitive Sciences*, *7*(2), 77-83. doi:https://doi.org/10.1016/S1364-6613(02)00025-6

Garcia-Willingham, N. E., Roach, A. R., Kasarskis, E. J., & Segerstrom, S. C. (2018). Self-Regulation and Executive Functioning as Related to Survival in Motor Neuron Disease: Preliminary Findings. *Psychosom Med*, *80*(7), 665-672. doi:10.1097/PSY.0000000000000602

Georgescu, A. L., Kuzmanovic, B., Roth, D., Bente, G., & Vogeley, K. (2014). The use of virtual characters to assess and train non-verbal communication in high-functioning autism. *Frontiers in human neuroscience, 8*.

Gerardi, M., Rothbaum, B. O., Ressler, K., Heekin, M., & Rizzo, A. (2008). Virtual reality exposure therapy using a virtual Iraq: case report. *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies*, *21*(2), 209-213.

Gillespie, S. M., & Beech, A. R. (2016). Theories of emotion regulation. *The Wiley handbook on the theories, assessment and treatment of sexual offending*, 245-263.

Goffman, E. (2017). Interaction ritual: Essays in face-to-face behavior: Routledge.

Goldin, P. R., McRae, K., Ramel, W., & Gross, J. J. (2008). The neural bases of emotion regulation: reappraisal and suppression of negative emotion. *Biological psychiatry*, *63*(6), 577-586.

Goudie, A. S. (2018). Human impact on the natural environment: *John Wiley & Sons*.

Grandey, A. A. (2000). Emotional regulation in the workplace: A new way to conceptualize emotional labor. *Journal of occupational health psychology*, *5*(1), 95.

Granic, I., Lobel, A., & Engels, R. C. (2014). The benefits of playing video games. *American psychologist*, *69*(1), 66.

Green, M. F., Horan, W. P., & Lee, J. (2015). Social cognition in schizophrenia. *Nature Reviews Neuroscience*.

Gross, J. J. (2002). Emotion regulation: Affective, cognitive, and social consequences. *Psychophysiology, 39*(3), 281-291. doi:10.1017/S0048577201393198.

Grossmann, T. (2013). The role of medial prefrontal cortex in early social cognition. *Frontiers in Human Neuroscience*, 7, 340.

Gweon, H., & Saxe, R. (2013). Developmental cognitive neuroscience of theory of mind. *Neural circuit development and function in the brain*, 367-377.

Hallgren, M., Pope Jr, H. G., Kanayama, G., Hudson, J. I., Lundin, A., & Källmén, H. (2015). Anti-Social Behaviors Associated with Anabolic-Androgenic Steroid Use among Male Adolescents. *European addiction research, 21*(6), 321-326.

Hammock, G. S., Richardson, D. S., Williams, C., & Janit, A. S. (2015). Perceptions of psychological and physical aggression between heterosexual partners. *Journal of Family Violence, 30*(1), 13-26.

Hample, D., & Anagondahalli, D. (2015). Understandings of arguing in India and the United States: Argument frames, personalization of conflict, argumentativeness, and verbal aggressiveness. *Journal of Intercultural Communication Research, 44*(1), 1-26.

Hampshire, A., Chamberlain, S. R., Monti, M. M., Duncan, J., & Owen, A. M. (2010). The role of the right inferior frontal gyrus: inhibition and attentional control. *Neuroimage, 50*(3), 1313-1319.

Han, J., Campbell, N., Jokinen, K., & Wilcock, G. (2012, December). Investigating the use of non-verbal cues in human-robot interaction with a Nao robot. In *2012 IEEE 3rd International Conference on Cognitive Infocommunications (CogInfoCom)* (pp. 679-683). IEEE.

Hari, R., Henriksson, L., Malinen, S., & Parkkonen, L. (2015). Centrality of social interaction in human brain function. *Neuron*, *88*(1), 181-193.

Haring, K. S., Matsumoto, Y., & Watanabe, K. (2013). How do people perceive and trust a lifelike robot. In *Proceedings of the world congress on engineering and computer science* (Vol. 1).

Haynes, B. (2017). Please Ignore Those Gestures: Does Warning Reduce the Gestural Misinformation Effect?

He, F., & Han, S. (2006). A method and tool for human–human interaction and instant collaboration in CSCW-based CAD. *Computers in Industry, 57*(8-9), 740-751.

Hill, D. B. (2006). Theory in applied social psychology: Past mistakes and future hopes. *Theory & Psychology,* 16(5), 613-640.

Hoffman, H. G., Richards, T. L., Coda, B., Bills, A. R., Blough, D., Richards, A. L., & Sharar, S. R. (2004). Modulation of thermal pain-related brain activity with virtual reality: evidence from fMRI. *Neuroreport, 15*(8), 1245-1248.

Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research, 55*(4), 270-279.

Honan, C. A., Skye, M., Fisher, A., & Osborne-Crowley, K. (2015). Social disinhibition: Piloting a new clinical measure in traumatic brain injury (TBI) individuals. In *INS/ASSBI 5th Pacific Rim Conference*.

Honan, C. A., Allen, S. K., Fisher, A., Osborne-Crowley, K., & McDonald, S. (2017). Social disinhibition: Piloting a new clinical measure in individuals with traumatic brain injury. *Brain Impairment*, *18*(1), 74-87.

Houdé, O., & Borst, G. (2015). Evidence for an inhibitory-control theory of the reasoning brain. *Frontiers in human neuroscience, 9,* 148-148. doi:10.3389/fnhum.2015.00148.

Hovik, K. T., Plessen, K. J., Skogli, E. W., Andersen, P. N., & Øie, M. (2013). Dissociable response inhibition in children with Tourette’s syndrome compared with children with ADHD. *Journal of attention disorders*, 1087054713512371.

Howell, A. N., Zibulsky, D. A., Srivastav, A., & Weeks, J. W. (2016). Relations among social anxiety, eye contact avoidance, state anxiety, and perception of interaction performance during a live conversation. *Cognitive behaviour therapy, 45*(2), 111-122.

Huang, K., Sparto, P. J., Kiesler, S., Smailagic, A., Mankoff, J., & Siewiorek, D. (2014, April). A technology probe of wearable in-home computer-assisted physical therapy. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2541-2550).

Huettel, S. A., Song, A. W., & McCarthy, G. (2004). *Functional magnetic resonance imaging* (Vol. 1): Sinauer Associates Sunderland, MA.

Hughes, S. O., Power, T. G., O'Connor, T. M., & Orlet Fisher, J. (2015). Executive functioning, emotion regulation, eating self-regulation, and weight status in low-income preschool children: how do they relate? *Appetite, 89*, 1-9. doi:10.1016/j.appet.2015.01.009

Hussain, L., Shafi, I., Saeed, S., Abbas, A., Awan, I. A., Nadeem, S. A., . . . Rahman, B. (2017). A radial base neural network approach for emotion recognition in human speech. *IJCSNS, 17*(8), 52.

Infante, D. A., & Wigley III, C. J. (1986). Verbal aggressiveness: An interpersonal model and measure. *Communications Monographs, 53*(1), 61-69.

Isaac, W. L., Nonneman, A. J., Neisewander, J., Landers, T., & Bardo, M. T. (1989). Prefrontal cortex lesions differentially disrupt cocaine-reinforced conditioned place preference but not conditioned taste aversion. *Behavioral neuroscience, 103*(2), 345.

Ip, H. H., Wong, S. W., Chan, D. F., Byrne, J., Li, C., Yuan, V. S., . . . Wong, J. Y. (2018). Enhance emotional and social adaptation skills for children with autism spectrum disorder: A virtual reality enabled approach. *Computers & Education, 117*, 1-15.

Jansen, A. S., Van Nguyen, X., Karpitskiy, V., Mettenleiter, T. C., & Loewy, A. D. (1995). Central command neurons of the sympathetic nervous system: basis of the fight-or-flight response. *Science*, 270(5236), 644-646.

Jiang, J., Bailey, K., Xiang, L., Zhang, L., & Zhang, Q. (2016). Comparing the Neural Correlates of Conscious and Unconscious Conflict Control in a Masked Stroop Priming Task. *Frontiers in Human Neuroscience, 10*, 297.

Jones, E. E. (1998). Major developments in five decades of social psychology.

Joormann, J., & Gotlib, I. H. (2010). Emotion regulation in depression: relation to cognitive inhibition. *Cognition and Emotion, 24*(2), 281-298.

Kacperck, L. (1997). Non-verbal communication: the importance of listening. *British Journal of Nursing*, *6*(5), 275-279.

Kamarajan, C., Porjesz, B., Jones, K., Chorlian, D., Padmanabhapillai, A., Rangaswamy, M., . . . Begleiter, H. (2006). Event-related oscillations in offspring of alcoholics: neurocognitive disinhibition as a risk for alcoholism. *Biological psychiatry, 59*(7), 625-634.

Kang, S. H., Gratch, J. J. C. A., & Worlds, V. (2010). Virtual humans elicit socially anxious interactants' verbal self-disclosure. *21*(3-4), 473-482.

Kanwisher, N. (2010). Functional specificity in the human brain: a window into the functional architecture of the mind. *Proceedings of the National Academy of Sciences*, 107(25), 11163-11170.

Karasewich, T. A., & Kuhlmeier, V. A. (2019). Trait Social Anxiety as a Conditional Adaptation: A Developmental and Evolutionary Framework.

Keltner, D., & Cordaro, D. T. (2017). Understanding multimodal emotional expressions: Recent advances in basic emotion theory. *The science of facial expression*, 57-75.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3), 203-220.

Kenny, P., Parsons, T. D., Gratch, J., Leuski, A., & Rizzo, A. A. (2007). *Virtual patients for clinical therapist skills training.* Paper presented at the International Workshop on Intelligent Virtual Agents.

Kesner, R. P., Farnsworth, G., & DiMattia, B. V. (1989). Double dissociation of egocentric and allocentric space following medial prefrontal and parietal cortex lesions in the rat. *Behavioral neuroscience,* 103(5), 956.

Kiani, F., Balouchi, A., & Shahsavani, A. (2016). Investigation of nursing students' verbal communication quality during patients' education in zahedan hospitals: Southeast of Iran. *Global journal of health science, 8*(9), 331.

Kim, N. Y., Wittenberg, E., & Nam, C. S. (2017). Behavioral and neural correlates of executive function: interplay between inhibition and updating processes. *Frontiers in neuroscience, 11*, 378.

Kimble, G. A. (1949). An experimental test of a two-factor theory of inhibition. *Journal of Experimental Psychology, 39*(1), 15.

KISS, Bemadette, B. Balázs, and Gábor Szijart. "VR-based Therapy." *Medicine Meets Virtual Reality 12: Building a Better You: The Next Tools for Medical Education, Diagnosis, and Care* 98 (2004): 16-30. *98*, 154.

Kilteni, K., Bergstrom, I., & Slater, M. (2013). Drumming in immersive virtual reality: the body shapes the way we play. *IEEE transactions on visualization and computer graphics*, 19(4), 597-605.

Klein, C. (2010). Philosophical Issues in Neuroimaging. *Philosophy Compass, 5*(2), 186-198. doi:10.1111/j.1747-9991.2009.00275.x

Knapp, M. L., Hall, J. A., & Horgan, T. G. (2013). *Nonverbal communication in human interaction*: Cengage Learning.

Koechlin, E., & Summerfield, C. (2007). An information theoretical approach to prefrontal executive function. *Trends in cognitive sciences*, *11*(6), 229-235.

Koch, C., Massimini, M., Boly, M., & Tononi, G. (2016). Neural correlates of consciousness: progress and problems. *Nature Reviews Neuroscience, 17*(5), 307-321.

Kozak, J. J., Hancock, P. A., Arthur, E. J., & Chrysler, S. T. (1993). Transfer of training from virtual reality. *Ergonomics*, 36(7), 777-784.

Kubota, K., & Niki, H. (1971). Prefrontal cortical unit activity and delayed alternation performance in monkeys. *Journal of neurophysiology*, 34(3), 337-347.

Løvstad, M., Funderud, I., Endestad, T., Due-Tønnessen, P., Meling, T. R., Lindgren, M., ... & Solbakk, A. K. (2012). Executive functions after orbital or lateral prefrontal lesions: neuropsychological profiles and self-reported executive functions in everyday living. *Brain Injury*, *26*(13-14), 1586-1598.

Landowska, A., Roberts, D., Eachus, P., & Barrett, A. (2018). Within-and between-session prefrontal cortex response to Virtual Reality Exposure Therapy for acrophobia. *Frontiers in Human Neuroscience, 12*.

Landowska, A., Roberts, D. J., & Eachus, P. (2017). Neural basis of virtual reality exposure threatment. *Annual Review of Cybertherapy and Telemedicine*, *15*, 16-18.

Landowska, A., Royle, S., Eachus, P., & Roberts, D. (2018). Testing the Potential of Combining Functional Near-Infrared Spectroscopy with Different Virtual Reality Displays—Oculus Rift and oCtAVE. In *Augmented Reality and Virtual Reality* (pp. 309-321): Springer.

Langerak, R. M., Prince, K., Herdman, C. M., & Wade, J. (2016). Embodiment in virtual reality. *Can J Exp Psychol*, *70*(4), 388.Lantz, E. J. A. S. C. G. (1997). Future directions in visual display systems. *31*(2), 38-42.

Lavorgna, L., Russo, A., De Stefano, M., Lanzillo, R., Esposito, S., Moshtari, F., . . . Morra, V. B. (2017). Health-Related Coping and Social Interaction in People with Multiple Sclerosis Supported by a Social Network: Pilot Study With a New Methodological Approach. *Interactive journal of medical research, 6*(2).

Leavitt, A., Keegan, B. C., & Clark, J. (2016, May). Ping to win? non-verbal communication and team performance in competitive online multiplayer games. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 4337-4350).

Lee, I. S., Preissl, H., & Enck, P. (2017). How to perform and interpret functional magnetic resonance imaging studies in functional gastrointestinal disorders. *Journal of neurogastroenterology and motility*, *23*(2), 197.

Liao, T., & Humphreys, L. (2015). Layar-ed places: Using mobile augmented reality to tactically reengage, reproduce, and reappropriate public space. *new media & society*, *17*(9), 1418-1435.

Lindblom, J. (2015). Embodiment and social interaction. In *Embodied social cognition* (pp. 115-159). Springer, Cham.

Liu, X., Banich, M. T., Jacobson, B. L., & Tanabe, J. L. (2004). Common and distinct neural substrates of attentional control in an integrated Simon and spatial Stroop task as assessed by event-related fMRI. *Neuroimage, 22*(3), 1097-1106.

Locascio, G., Mahone, E. M., Eason, S. H., & Cutting, L. E. (2010). Executive dysfunction among children with reading comprehension deficits. *Journal of learning disabilities*, *43*(5), 441-454.

Logothetis, N. K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A. (2001). Neurophysiological investigation of the basis of the fMRI signal. *Nature, 412*(6843), 150-157.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior research methods, instruments, & computers*, *31*(4), 557-564.

Lorenzo, G., Lledó, A., Pomares, J., & Roig, R. (2016). Design and application of an immersive virtual reality system to enhance emotional skills for children with autism spectrum disorders. *Computers & Education*, *98*, 192-205.

Lozada, F. T., Halberstadt, A. G., Craig, A. B., Dennis, P. A., & Dunsmore, J. C. (2016). Parents' beliefs about children's emotions and parents' emotion-related conversations with their children. *Journal of Child and Family Studies, 25*(5), 1525-1538.

Lu, C.-M., Zhang, Y.-J., Biswal, B. B., Zang, Y.-F., Peng, D.-L., & Zhu, C.-Z. (2010). Use of fNIRS to assess resting state functional connectivity. *Journal of Neuroscience Methods, 186*(2), 242-249. doi:https://doi.org/10.1016/j.jneumeth.2009.11.010.

Mayer, R. E. (2002). Multimedia learning. *Psychology of learning and motivation*, *41*, 85-139.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the Role of the Dorsolateral Prefrontal and Anterior Cingulate Cortex in Cognitive Control. *Science, 288*(5472), 1835-1838. doi:10.1126/science.288.5472.1835

Mahy, C. E. V., Moses, L. J., & Pfeifer, J. H. (2014). How and where: Theory-of-mind in the brain. *Developmental Cognitive Neuroscience, 9*, 68-81. doi:https://doi.org/10.1016/j.dcn.2014.01.002

Martínez, Á. N. (2016). The contrast of the Spanish gestures with other cultures: communicative and intercultural competence in teaching Spanish. *Иберoамериканские тетради, 1*(2), 522-533.

Markowitsch, H. J., & Pritzel, M. (1978). The insular region: Part of the prefrontal cortex?. *Neuroscience & Biobehavioral Reviews*, 2(4), 271-276.

Matsumoto, D. (2006). Culture and nonverbal behavior. *Handbook of nonverbal communication*, 219-235.

McBride, T., Arnold, S. E., & Gur, R. C. (1999). A comparative volumetric analysis of the prefrontal cortex in human and baboon MRI. *Brain, behavior and evolution*, 54(3), 159-166.

Miller, B. L., Darby, A., Benson, D. F., Cummings, J. L., & Miller, M. H. (1997). Aggressive, socially disruptive and antisocial behaviour associated with fronto-temporal dementia. *The British journal of psychiatry*, 170(2), 150-155.

Miller, B. (2017, December). Wrongful Moves in Unfamiliar Meaning Spaces: Gesture Usage and Implications for Cross-Cultural Gestural-Pragmatic Failure. In *Outside the Box: A Multi-Lingual Forum* (p. 7).

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience*, *24*(1), 167-202.

Miller, E. K., & Wallis, J. D. (2009). Executive function and higher-order cognition: definition and neural substrates. *Encyclopedia of neuroscience*, 4(99-104).

Minzenberg, M. J., Laird, A. R., Thelen, S., Carter, C. S., & Glahn, D. C. (2009). Meta-analysis of 41 functional neuroimaging studies of executive function in schizophrenia. *Archives of general psychiatry*, 66(8), 811-822.

Morawski, J. G. (2000). Social psychology a century ago. *American Psychologist*, 55(4), 427.

Morina, N., Ijntema, H., Meyerbröker, K., & Emmelkamp, P. M. (2015). Can virtual reality exposure therapy gains be generalized to real-life? A meta-analysis of studies applying behavioral assessments. *Behaviour research and therapy*, *74*, 18-24.

Moskowitz, D. S. (1993). Dominance and friendliness: On the interaction of gender and situation. *Journal of Personality*, *61*(3), 387-409.

Murray, E. A., Wise, S. P., & Graham, K. S. (2017). *The evolution of memory systems: ancestors, anatomy, and adaptations*. Oxford University Press.

Murugan, M., Jang, H. J., Park, M., Miller, E. M., Cox, J., Taliaferro, J. P., ... & Nectow, A. R. (2017). Combined social and spatial coding in a descending projection from the prefrontal cortex. *Cell*, *171*(7), 1663-1677.

Nakada, M., Chen, H., & Terzopoulos, D. (2018, August). Deep learning of biomimetic visual perception for virtual humans. In *Proceedings of the 15th ACM Symposium on Applied Perception* (pp. 1-8).

Narayanan, N. S., & Laubach, M. (2017). Inhibitory Control: Mapping Medial Frontal Cortex. *Current Biology*, *27*(4), R148-R150.

Nathaniel-James, D., Fletcher, P., & Frith, C. (1997). The functional anatomy of verbal initiation and suppression using the Hayling Test. *Neuropsychologia*, *35*(4), 559-566.

Ng, T. T., Chang, S. F., & Tsui, M. P. (2007, April). Lessons learned from online classification of photo-realistic computer graphics and photographs. In 2007 IEEE Workshop on Signal Processing Applications for Public Security and Forensics (pp. 1-6). *IEEE*.

Niki, C., Maruyama, T., Muragaki, Y., & Kumada, T. (2009). Disinhibition of sequential actions following right frontal lobe damage. *Cognitive neuropsychology*, 26(3), 266-285.

Nikolaidis, S., Kwon, M., Forlizzi, J., & Srinivasa, S. (2017). Planning with Verbal Communication for Human-Robot Collaboration. *arXiv preprint arXiv:1706.04694*.

Nolin, P., Stipanicic, A., Henry, M., Lachapelle, Y., Lussier-Desrochers, D., Rizzo, A. S., & Allain, P. (2016). ClinicaVR: Classroom-CPT: A virtual reality tool for assessing attention and inhibition in children and adolescents. *Computers in Human Behavior*, *59*, 327-333. doi:http://dx.doi.org/10.1016/j.chb.2016.02.023.

North, M. M., & North, S. M. (2016). Virtual reality therapy. *Computer-Assisted and Web-Based Innovations in Psychology, Special Education, and Health*, 141.

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *proceedings of the National Academy of Sciences*, *87*(24), 9868-9872.

Oh, H. K., Park, S. J., Bae, S. G., Kim, M. J., Jang, J. H., Ahn, Y. J., . . . Ryu, J. H. (2013). Kami-ondam-tang, a traditional herbal prescription, attenuates the prepulse inhibition deficits and cognitive impairments induced by MK-801 in mice. *J Ethnopharmacol, 146*(2), 600-607. doi:10.1016/j.jep.2013.01.032

Osterlund, J., & Lawrence, B. (2012). Virtual reality: Avatars in human spaceflight training. *Acta Astronautica*, *71*, 139-150.

Owen, A. M. (2000). The role of the lateral frontal cortex in mnemonic processing: the contribution of functional neuroimaging. *Experimental brain research*, *133*(1), 33-43.

Papadelis, C., Grant, P. E., Okada, Y., & Preissl, H. (Eds.). (2015). *Magnetoencephalography: an emerging neuroimaging tool for studying normal and abnormal human brain development*. Frontiers Media SA.

Pausch, R., Proffitt, D., & Williams, G. (1997, August). Quantifying immersion in virtual reality. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (pp. 13-18).

Pease, A., & Pease, B. (2016). *The Definitive Book of Body Language: how to read others' attitudes by their gestures*: Hachette UK.

Peelle, J. E. (2019). The neural basis for auditory and audiovisual speech perception.

Pepler, D. J., Madsen, K. C., Webster, C. D., & Levene, K. S. (Eds.). (2014). *The development and treatment of girlhood aggression*. Psychology Press.

Pérez-Pérez, A., Matias-Guiu, J. A., Cáceres-Guillén, I., Rognoni, T., Valles-Salgado, M., Fernández-Matarrubia, M., . . . Matías-Guiu, J. (2016). The Hayling Test: Development and Normalization of the Spanish Version. *Archives of Clinical Neuropsychology*, acw027.

Pfurtscheller, G., Schwerdtfeger, A., Seither-Preisler, A., Brunner, C., Aigner, C. S., Calisto, J., ... & Andrade, A. (2018). Synchronization of intrinsic 0.1-Hz blood-oxygen-level-dependent oscillations in amygdala and prefrontal cortex in subjects with increased state anxiety. *European journal of neuroscience*, *47*(5), 417-426.

Pinkham, A. E., Griffin, M., Baron, R., Sasson, N. J., & Gur, R. C. (2010). The face in the crowd effect: anger superiority when using real faces and multiple identities. *Emotion*, *10*(1), 141.

Piron, L., Cennis, F., Tonins, P., & Dam, M. (2001). Virtual Reality as an assessment tool. In *Medicine Meets Virtual Reality* (Vol. 2001, No. 81, p. 386).

Powers, M. B., & Emmelkamp, P. M. (2008). Virtual reality exposure therapy for anxiety disorders: A meta-analysis. *Journal of anxiety disorders*, *22*(3), 561-569.

Psotka, J. (1995). Immersive training systems: Virtual reality and education and training. *Instructional Science*, *23*(5), 405-431. doi:10.1007/bf00896880.

Quirk, G. J., Likhtik, E., Pelletier, J. G., & Paré, D. (2003). Stimulation of medial prefrontal cortex decreases the responsiveness of central amygdala output neurons. *Journal of Neuroscience*, *23*(25), 8800-8807.

Raij, A.B., Johnsen, K., Dickerson, R.F., Lok, B.C., Cohen, M.S., Duerson, M., Pauly, R.R., Stevens, A.O., Wagner, P. and Lind, D.S., 2007. Comparing interpersonal interactions with a virtual human to those with a real human. *IEEE transactions on visualization and computer graphics*, 13(3), pp.443-457.

Ramos-Loyo, J., González-Garrido, A. A., García-Aguilar, G., & Del Río-Portilla, Y. (2013). The emotional content of faces interferes with inhibitory processing: an event related potential study. *International Journal of Psychological Studies*, *5*(2), 52.

Ray, R. D., Ochsner, K. N., Cooper, J. C., Robertson, E. R., Gabrieli, J. D. E., & Gross, J. J. (2005). Individual differences in trait rumination and the neural systems supporting cognitive reappraisal. *Cognitive, Affective, & Behavioral Neuroscience, 5*(2), 156-168. doi:10.3758/cabn.5.2.156

Reinecke, A., Thilo, K., Filippini, N., Croft, A., & Harmer, C. J. (2014). Predicting rapid response to cognitive-behavioural treatment for panic disorder: the role of hippocampus, insula, and dorsolateral prefrontal cortex. *Behaviour research and therapy*, *62*, 120-128.

Remland, M. S., Jones, T. S., & Brinkman, H. (1995). Interpersonal Distance, Body Orientation, and Touch: Effects of Culture, Gender, and Age. *The Journal of Social Psychology, 135*(3), 281-297. doi:10.1080/00224545.1995.9713958

Ridderinkhof, K. R., Van Den Wildenberg, W. P., Segalowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain and cognition*, *56*(2), 129-140.

Riggio, R. E. (1992). Social interaction skills and nonverbal behavior. *Applications of nonverbal behavioral theories and research*, 3-30.

Rilling, J., & Sanfey, A. (2009). Social interaction.

Rilling, J. K., & Sanfey, A. G. (2009). The neuroscience of social decision-making. *Annual review of psychology*, *62*, 23-48.

Ritaetal, G. (1998). IMMERSIVENESS ON PHYSIOLOGY. *Virtual Environments in Clinical Psychology and Neuroscience: Methods and Techniques in Advanced Patient-therapist Interaction*, *58*, 52.

Ritz, L. T., & Buss, A. R. (2016). A Framework for Aligning Instructional Design Strategies with Affordances of CAVE Immersive Virtual Reality Systems. *TechTrends*, *60*(6), 549-556.

Rizzo, A. A., Bowerly, T., Buckwalter, J. G., Klimchuk, D., Mitura, R., & Parsons, T. D. (2009). A virtual reality scenario for all seasons: the virtual classroom. *Cns Spectrums*, 11(1), 35-44.

Robitaille, N., Jackson, P. L., Hébert, L. J., Mercier, C., Bouyer, L. J., Fecteau, S., . . . McFadyen, B. J. (2016). A Virtual Reality avatar interaction (VRai) platform to assess residual executive dysfunction in active military personnel with previous mild traumatic brain injury: proof of concept. *Disability and Rehabilitation: Assistive Technology*, 1-7.

Romero, E., Luengo, M. A., & Sobral, J. (2001). Personality and antisocial behaviour: Study of temperamental dimensions. *Personality and individual differences*, 31(3), 329-348.

Rose, F. D., Attree, E. A., Brooks, B. M., Parslow, D. M., & Penn, P. R. (2000). Training in virtual environments: transfer to real world tasks and equivalence to real task training. *Ergonomics*, 43(4), 494-511.

Roth, R. M., Randolph, J. J., Koven, N. S., & Isquith, P. K. (2006). Neural Substrates of Executive Functions: Insights from Functional Neuroimaging.

Rothbaum, B. O., Hodges, L. F., Ready, D., Graap, K., & Alarcon, R. D. (2001). Virtual reality exposure therapy for Vietnam veterans with posttraumatic stress disorder. *The Journal of clinical psychiatry*.

Sakaguchi, S. (2005). Naturally arising Foxp3-expressing CD25+ CD4+ regulatory T cells in immunological tolerance to self and non-self. *Nature immunology*, *6*(4), 345-352.

Saleh, G. M., Theodoraki, K., Gillan, S., Sullivan, P., O'sullivan, F., Hussain, B., ... & Athanasiadis, I. (2013). The development of a virtual reality training programme for ophthalmology: repeatability and reproducibility (part of the International Forum for Ophthalmic Simulation Studies). *Eye*, *27*(11), 1269-1274.

Salem, B., & Earle, N. (2000, September). Designing a non-verbal language for expressive avatars. In *Proceedings of the third international conference on Collaborative virtual environments* (pp. 93-101).

Sani, S. R. H., Tabibi, Z., Fadardi, J. S., & Stavrinos, D. (2017). Aggression, emotional self-regulation, attentional bias, and cognitive inhibition predict risky driving behavior. *Accid Anal Prev, 109*, 78-88. doi:10.1016/j.aap.2017.10.006

Santos, B. S., Dias, P., Pimentel, A., Baggerman, J. W., Ferreira, C., Silva, S., & Madeira, J. (2009). Head-mounted display versus desktop for 3D navigation in virtual reality: a user study. *Multimedia tools and applications, 41(1)*, 161.

Schilbach, L., Wohlschlaeger, A. M., Kraemer, N. C., Newen, A., Shah, N. J., Fink, G. R., & Vogeley, K. (2006a). Being with virtual others: Neural correlates of social interaction. *Neuropsychologia*, *44*(5), 718-730.

Schroeter, M. L., Kupka, T., Mildner, T., Uludağ, K., & von Cramon, D. Y. (2006). Investigating the post-stimulus undershoot of the BOLD signal—a simultaneous fMRI and fNIRS study. *Neuroimage*, *30*(2), 349-358.

Schulze, L., Domes, G., Krüger, A., Berger, C., Fleischer, M., Prehn, K., ... & Herpertz, S. C. (2011). Neuronal correlates of cognitive reappraisal in borderline patients with affective instability. *Biological psychiatry*, *69*(6), 564-573.

Serrano-Ibanez, E. R., Ramirez-Maestre, C., Lopez-Martinez, A. E., Esteve, R., Ruiz-Parraga, G. T., & Jensen, M. P. (2018). Behavioral Inhibition and Activation Systems, and Emotional Regulation in Individuals With Chronic Musculoskeletal Pain. *Front Psychiatry, 9,* 394. doi:10.3389/fpsyt.2018.00394.

Sebanz, N., Knoblich, G., & Prinz, W. (2003). Representing others' actions: just like one's own? *Cognition*, *88*(3), B11-B21.

Shaban, N., & Kumar, P. (2016). Young Adults and Aggression: A Comparative Study of Gender Differences. *The International Journal of Indian Psychology, Volume 3, Issue 4, No. 57,* 106.

Shackman, A. J., McMenamin, B. W., Maxwell, J. S., Greischar, L. L., & Davidson, R. J. (2009). Right dorsolateral prefrontal cortical activity and behavioral inhibition. *Psychological science*, *20*(12), 1500-1506.

Sharples, S., Cobb, S., Moody, A., & Wilson, J. R. (2008). Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays*, *29*(2), 58-69.

Shields, G. S., Bonner, J. C., & Moons, W. G. (2015). Does cortisol influence core executive functions? A meta-analysis of acute cortisol administration effects on working memory, inhibition, and set-shifting. *Psychoneuroendocrinology*, *58*, 91-103.

Simon, H. A. (1952). A formal theory of interaction in social groups. *American Sociological Review, 17*(2), 202-211.

Singer, T., Seymour, B., O'Doherty, J. P., Stephan, K. E., Dolan, R. J., & Frith, C. D. (2006). Empathic neural responses are modulated by the perceived fairness of others. *Nature*, 439(7075), 466.

Skarratt, P. A., Cole, G. G., & Kingstone, A. (2010). Social inhibition of return. *Acta psychologica*, 134(1), 48-54.

Slater, M., Rovira, A., Southern, R., Swapp, D., Zhang, J. J., Campbell, C., & Levine, M. (2013). Bystander responses to a violent incident in an immersive virtual environment. *PloS one*, 8(1).

Sliwa, J., & Freiwald, W. A. (2017). A dedicated network for social interaction processing in the primate brain. *Science*, *356*(6339), 745-749.

Smit, J. C., & vanderVen, A. H. G. S. (1995). Inhibition in Speed and Concentration Tests: The Poisson Inhibition Model. *Journal of Mathematical Psychology, 39*(3), 265-274. doi:https://doi.org/10.1006/jmps.1995.1027

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science*, *283*(5408), 1657-1661.

Smith, P. K., Pepler, D. J., & Rigby, K. (2004). *Bullying in schools : how successful can interventions be?* New York: Cambridge University Press.

So, W. C., Wong, M. K. Y., & Lam, K. Y. (2016, November). Social and communication skills predict imitation abilities in children with autism. In *Frontiers in Education* (Vol. 1, p. 3). Frontiers.

Song, J. H., Volling, B. L., Lane, J. D., & Wellman, H. M. (2016). Aggression, sibling antagonism, and theory of mind during the first year of siblinghood: a developmental cascade model. *Child development*.

Song, Y., & Hakoda, Y. (2015). An fMRI study of the functional mechanisms of Stroop/reverse-Stroop effects. *Behavioural Brain Research, 290,* 187-196. doi:http://dx.doi.org/10.1016/j.bbr.2015.04.047

Sorokowska, A., Sorokowski, P., Hilpert, P., Cantarero, K., Frackowiak, T., Ahmadi, K., ... & Blumen, S. (2017). Preferred interpersonal distances: a global comparison. *Journal of Cross-Cultural Psychology*, *48*(4), 577-592.

Spieler, C., & Miltenberger, R. (2017). Using awareness training to decrease nervous habits during public speaking. *Journal of applied behavior analysis, 50*(1), 38-47.

Spinrad, T. L., & Eisenberg, N. A. N. C. Y. (2014). Empathy, prosocial behavior, and positive development in schools.

Staudinger, M. R., Erk, S., & Walter, H. (2011). Dorsolateral prefrontal cortex modulates striatal reward encoding during reappraisal of reward anticipation. *Cerebral cortex*, *21*(11), 2578-2588.

Steegmann, A. T. (1962). Dr. Harlow's famous case: The “impossible” accident of Phineas P. Gage. *Surgery*, 52(6), 952-958.

Steinbeis, N. (2016). The role of self–other distinction in understanding others' mental and emotional states: neurocognitive mechanisms in children and adults. *Phil. Trans. R. Soc. B, 371*(1686), 20150074.

Steinicke, F., Bruder, G., Hinrichs, K., Lappe, M., Ries, B., & Interrante, V. (2009). *Transitional environments enhance distance perception in immersive virtual reality systems*. Paper presented at the Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization.

Stenbäck, V., Hällgren, M., & Larsby, B. (2016). Executive functions and working memory capacity in speech communication under adverse conditions. *Speech, Language and Hearing*, 1-9.

Stern, C. E., Owen, A. M., Tracey, I., Look, R. B., Rosen, B. R., & Petrides, M. (2000). Activity in ventrolateral and mid-dorsolateral prefrontal cortex during nonspatial visual working memory processing: evidence from functional magnetic resonance imaging. *NeuroImage*, *11*(5), 392-399.

Strait, M., & Scheutz, M. (2014). What we can and cannot (yet) do with functional near infrared spectroscopy. *Frontiers in Neuroscience, 8*, 117. doi:10.3389/fnins.2014.00117

Stramaccia, D. F., Penolazzi, B., Sartori, G., Braga, M., Mondini, S., & Galfano, G. (2015). Assessing the effects of tDCS over a delayed response inhibition task by targeting the right inferior frontal gyrus and right dorsolateral prefrontal cortex. *Experimental brain research*, *233*(8), 2283-2290.

Striedter, G. F. (2005). *Principles of brain evolution*. Sinauer associates.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of experimental psychology*, *18*(6), 643.

Stuss, D. T. (2011). Traumatic brain injury: relation to executive dysfunction and the frontal lobes. *Current opinion in neurology*, 24(6), 584-589.

Suda, M., Takei, Y., Aoyama, Y., Narita, K., Sato, T., Fukuda, M., & Mikuni, M. (2010). Frontopolar activation during face-to-face conversation: an in situ study using near-infrared spectroscopy. *Neuropsychologia*, 48(2), 441-447.

Suznjevic, M., Mandurov, M., & Matijasevic, M. (2017, May). Performance and QoE assessment of HTC Vive and Oculus Rift for pick-and-place tasks in VR. In *2017 Ninth International Conference on Quality of Multimedia Experience (QoMEX)* (pp. 1-3). IEEE.

Suzuki, M., Miyai, I., Ono, T., & Kubota, K. (2008). Activities in the frontal cortex and gait performance are modulated by preparation. An fNIRS study. *Neuroimage, 39*(2), 600-607.

Swartout, W.R., Gratch, J., Hill Jr, R.W., Hovy, E., Marsella, S., Rickel, J. and Traum, D., 2006. Toward virtual humans. *AI Magazine*, 27(2), pp.96-96.

Takei, Y., Suda, M., Aoyama, Y., Yamaguchi, M., Sakurai, N., Narita, K., ... & Mikuni, M. (2013). Temporal lobe and inferior frontal gyrus dysfunction in patients with schizophrenia during face-to-face conversation: a near-infrared spectroscopy study. *Journal of psychiatric research*, 47(11), 1581-1589.

Thalheimer, W., & Cook, S. (2002). How to calculate effect sizes from published research: A simplified methodology. *Work-Learning Research*, 1, 1-9.

Thiebaux, M., Marsella, S., Marshall, A. N., & Kallmann, M. (2008, May). Smartbody: Behavior realization for embodied conversational agents. In *Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems-Volume 1* (pp. 151-158).

Thomas, M., Sing, H., Belenky, G., Holcomb, H., Mayberg, H., Dannals, R., ... & Welsh, A. (2000). Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. *Journal of sleep research*, *9*(4), 335-352.

Tirapu-Ustarroz, J., Garcia-Molina, A., Luna-Lario, P., Roig-Rovira, T., & Pelegrin-Valero, C. (2008). Models of executive control and functions (I). *Revista de neurologia*, *46*(11), 684-692.

Underwood, M. K. (2004). III. Glares of contempt, eye rolls of disgust and turning away to exclude: Non-verbal forms of social aggression among girls. *Feminism & Psychology*, *14*(3), 371-375.

Vargo, J. M., Richard-Smith, M., & Corwin, J. V. (1989). Spiroperidol reinstates asymmetries in neglect in rats recovered from left or right dorsomedial prefrontal cortex lesions. *Behavioral neuroscience*, 103(5), 1017.

Verissimo, R., Mota-Cardoso, R., & Taylor, G. (1998). Relationships between alexithymia, emotional control, and quality of life in patients with inflammatory bowel disease. *Psychotherapy and psychosomatics*, *67*(2), 75-80.

Vlainic, E., Liepelt, R., Colzato, L. S., Prinz, W., & Hommel, B. (2009). The virtual co-actor: the social Simon effect does not rely on online feedback from the other. *Embodied and grounded cognition*, 102.

Vohs, K. D., Baumeister, R. F., Schmeichel, B. J., Twenge, J. M., Nelson, N. M., & Tice, D. M. (2014). Making choices impairs subsequent self-control: a limited-resource account of decision making, self-regulation, and active initiative.

Völlm, B. A., Taylor, A. N. W., Richardson, P., Corcoran, R., Stirling, J., McKie, S., . . . Elliott, R. (2006). Neuronal correlates of theory of mind and empathy: A functional magnetic resonance imaging study in a nonverbal task. *NeuroImage, 29*(1), 90-98. doi:https://doi.org/10.1016/j.neuroimage.2005.07.022

Wagner, A. D., Maril, A., Bjork, R. A., & Schacter, D. L. (2001). Prefrontal contributions to executive control: fMRI evidence for functional distinctions within lateral prefrontal cortex. *Neuroimage*, *14*(6), 1337-1347.

Walther, J. B., Van Der Heide, B., Ramirez, A., Burgoon, J. K., & Peña, J. (2015). Interpersonal and Hyperpersonal Dimensions of Computer-Mediated Communication. *The handbook of the psychology of communication technology*, 1-22.

Weiss, A., & Bartneck, C. (2015, August). Meta analysis of the usage of the godspeed questionnaire series. In *2015 24th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)* (pp. 381-388). IEEE.

Wendt, J., Neubert, J., Lindner, K., Ernst, F. D., Homuth, G., Weike, A. I., & Hamm, A. O. (2015). Genetic influences on the acquisition and inhibition of fear. *International Journal of Psychophysiology*, *98*(3), 499-505..

Westbury, H. R., & Neumann, D. L. (2008). Empathy-related responses to moving film stimuli depicting human and non-human animal targets in negative circumstances. *Biological psychology*, *78*(1), 66-74.

Williams, P. G. (2010). Self-regulation, executive functioning, and neurovisceral integration. *Pain, 151*(1), 5-6. doi:10.1016/j.pain.2010.05.010.

Yarczower, M., & Daruns, L. (1982). Social inhibition of spontaneous facial expressions in children. *Journal of Personality and Social Psychology*, 43(4), 831.

Yang, Y., & Raine, A. (2009). Prefrontal structural and functional brain imaging findings in antisocial, violent, and psychopathic individuals: a meta-analysis. *Psychiatry Research: Neuroimaging*, 174(2), 81-88.

Yang, Z., Kelly, C., Castellanos, F. X., Leon, T., Milham, M. P., & Adler, L. A. (2016). Neural Correlates of Symptom Improvement Following Stimulant Treatment in Adults with Attention-Deficit/Hyperactivity Disorder. *Journal of child and adolescent psychopharmacology*.

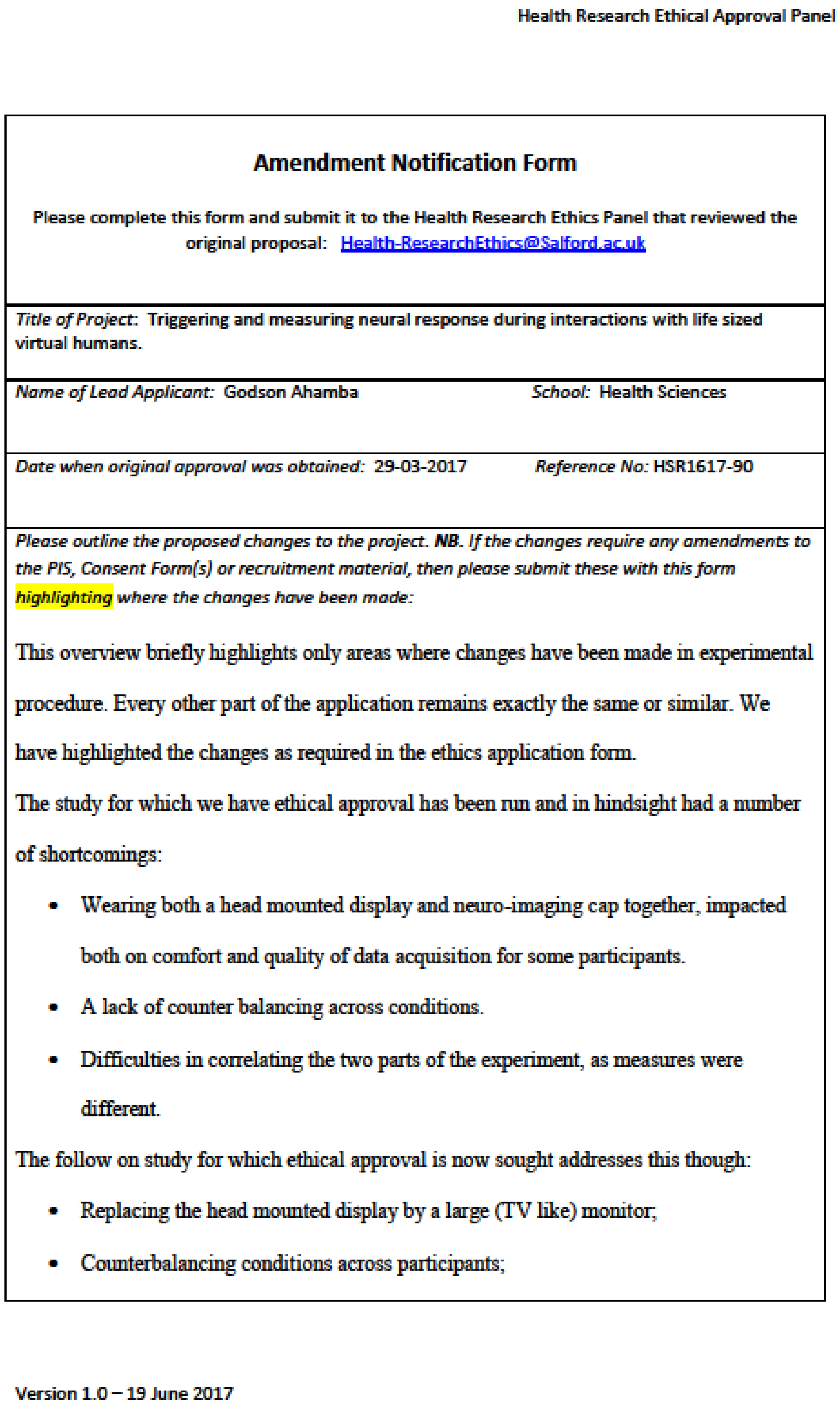
Yin, X., Xu, B., Jiang, C., Fu, Y., Wang, Z., Li, H., & Shi, G. (2015). A hybrid BCI based on EEG and fNIRS signals improves the performance of decoding motor imagery of both force and speed of hand clenching. *Journal of neural engineering, 12*(3), 036004. .

Young, M. K., Gaylor, G. B., Andrus, S. M., & Bodenheimer, B. (2014, August). A comparison of two cost-differentiated virtual reality systems for perception and action tasks. In *Proceedings of the ACM Symposium on Applied Perception* (pp. 83-90).

Yuan, P., & Raz, N. (2014). Prefrontal cortex and executive functions in healthy adults: a meta-analysis of structural neuroimaging studies. *Neuroscience & Biobehavioral Reviews, 42*, 180-192.

Zmigrod, S., Colzato, L. S., & Hommel, B. (2014). Evidence for a role of the right dorsolateral prefrontal cortex in controlling stimulus-response integration: a transcranial direct current stimulation (tDCS) study. *Brain stimulation, 7*(4), 516-520.

APPENDIX 1: Ethics Approval



Health Research Ethical Approval Panel

Amendment Notification Form

Please complete this form and submit it to the Health Research Ethics Panel that reviewed the original proposal: Health-ResearchEthics@Salford.ac.uk

Title of Project: Triggering and measuring neural response during interactions with life sized virtual humans.

Name of Lead Applicant: Godson Ahamba

School: Health Sciences

Date when original approval was obtained: 29-03-2017

Reference No: HSR1617-90

*Please outline the proposed changes to the project. **NB**. If the changes require any amendments to the PIS, Consent Form(s) or recruitment material, then please submit these with this form highlighting where the changes have been made:*

This overview briefly highlights only areas where changes have been made in experimental procedure. Every other part of the application remains exactly the same or similar. We have highlighted the changes as required in the ethics application form.

The study for which we have ethical approval has been run and in hindsight had a number of shortcomings:

- Wearing both a head mounted display and neuro-imaging cap together, impacted both on comfort and quality of data acquisition for some participants.
- A lack of counter balancing across conditions.
- Difficulties in correlating the two parts of the experiment, as measures were different.

The follow on study for which ethical approval is now sought addresses this though:

- Replacing the head mounted display by a large (TV like) monitor;
- Counterbalancing conditions across participants;

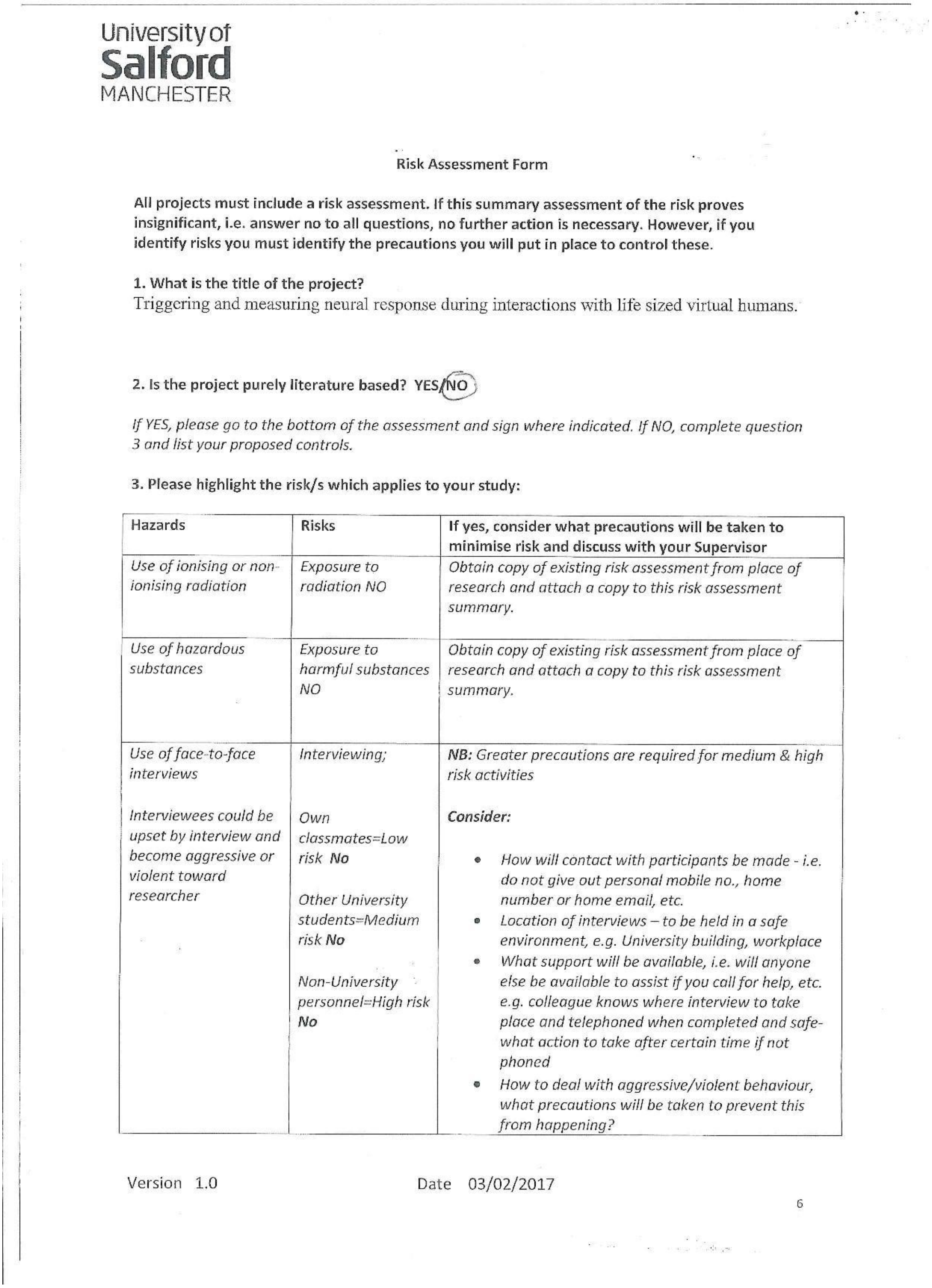
Version 1.0 – 19 June 2017

APPENDIX 2: Summary of Supervision Record

Date	Training & Development Activity	Self-evaluation
January 2016	N/A	Started off with Oculus Rift
February 2016	N/A	My confidence around the Research Area increased conspicuously with my supervisor expanding my scope and meeting with key figures around my Research area.
March 2016	1) Translating our diagnostic imaging research into practice (Seminar) 2) Perceptual Control Theory (Seminar)	Line of action bacame clearer and confidence improved.
April 2016	Locating and Using Historical Archives for Research	Confidence around my PhD kept increasing from talking about my PhD work with different groups of people.
May 2016	N/A	Shortlisted for a short talk in the VR conference.
June 2016	N/A	Getting more involved in the VR part of my research. Working on demos as well.
July 2016	2nd Virtual Social Interaction Workshop	PhD progress impressive.
August 2016	Webinar on writing a research paper	Happy with the progress of my PhD.
September 2016	N/A	Struggling with choosing an ideal experiment
October 2016	N/A	Attempted Augmented Reality implementation.
November 2016	N/A	Arranging my Interim report for submission.
January 2017	None	Learned a lot while trying to get ethics submitted
February 2017	SPSS Training	Built confidence with experimental design. However was challenged by the fact that I had to pay for most of the good tools
March 2017		Ethical approval obtained, was happy with progress, but was under pressure to complete experiment.
April 2017		Finally completed experiment for pilot.

May 2017		Felt under pressure to do a bit more, even though I was happy with progress of experiment.
June 2017	Cyber Psychology Conference (CYPSY 22).	Progress was good both with data gathering and poster presentation at CYPSY 22.
July 2017		Progres was encouraging
August 2017		Making progress
September 2017		Started looking into data gathered in details
October 2017	Manchester Science Festival	Good progress
November 2017		
June 2018	CYPSY 23 Talk	Presented my work at the CYPSY23 in Canada and it was an impressive outing.
April 2019	Paper Submission	Submitted manuscript to neuropsychologia.

APPENDIX 3: Risk Assessment



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Risk Assessment Form

All projects must include a risk assessment. If this summary assessment of the risk proves insignificant, i.e. answer no to all questions, no further action is necessary. However, if you identify risks you must identify the precautions you will put in place to control these.

1. What is the title of the project?

Triggering and measuring neural response during interactions with life sized virtual humans.

2. Is the project purely literature based? YES/[✓ NO]

If YES, please go to the bottom of the assessment and sign where indicated. If NO, complete question 3 and list your proposed controls.

3. Please highlight the risk/s which applies to your study:

Hazards	Risks	**If yes, consider what precautions will be taken to minimise risk and discuss with your Supervisor**
Use of ionising or non-ionising radiation	*Exposure to radiation NO*	*Obtain copy of existing risk assessment from place of research and attach a copy to this risk assessment summary.*
Use of hazardous substances	*Exposure to harmful substances NO*	*Obtain copy of existing risk assessment from place of research and attach a copy to this risk assessment summary.*
Use of face-to-face interviews *Interviewees could be upset by interview and become aggressive or violent toward researcher*	*Interviewing;* *Own classmates=Low risk* ***No*** *Other University students=Medium risk* ***No*** *Non-University personnel=High risk* ***No***	***NB:*** *Greater precautions are required for medium & high risk activities* ***Consider:*** • *How will contact with participants be made - i.e. do not give out personal mobile no., home number or home email, etc.* • *Location of interviews – to be held in a safe environment, e.g. University building, workplace* • *What support will be available, i.e. will anyone else be available to assist if you call for help, etc. e.g. colleague knows where interview to take place and telephoned when completed and safe-what action to take after certain time if not phoned* • *How to deal with aggressive/violent behaviour, what precautions will be taken to prevent this from happening?*

Version 1.0 Date 03/02/2017

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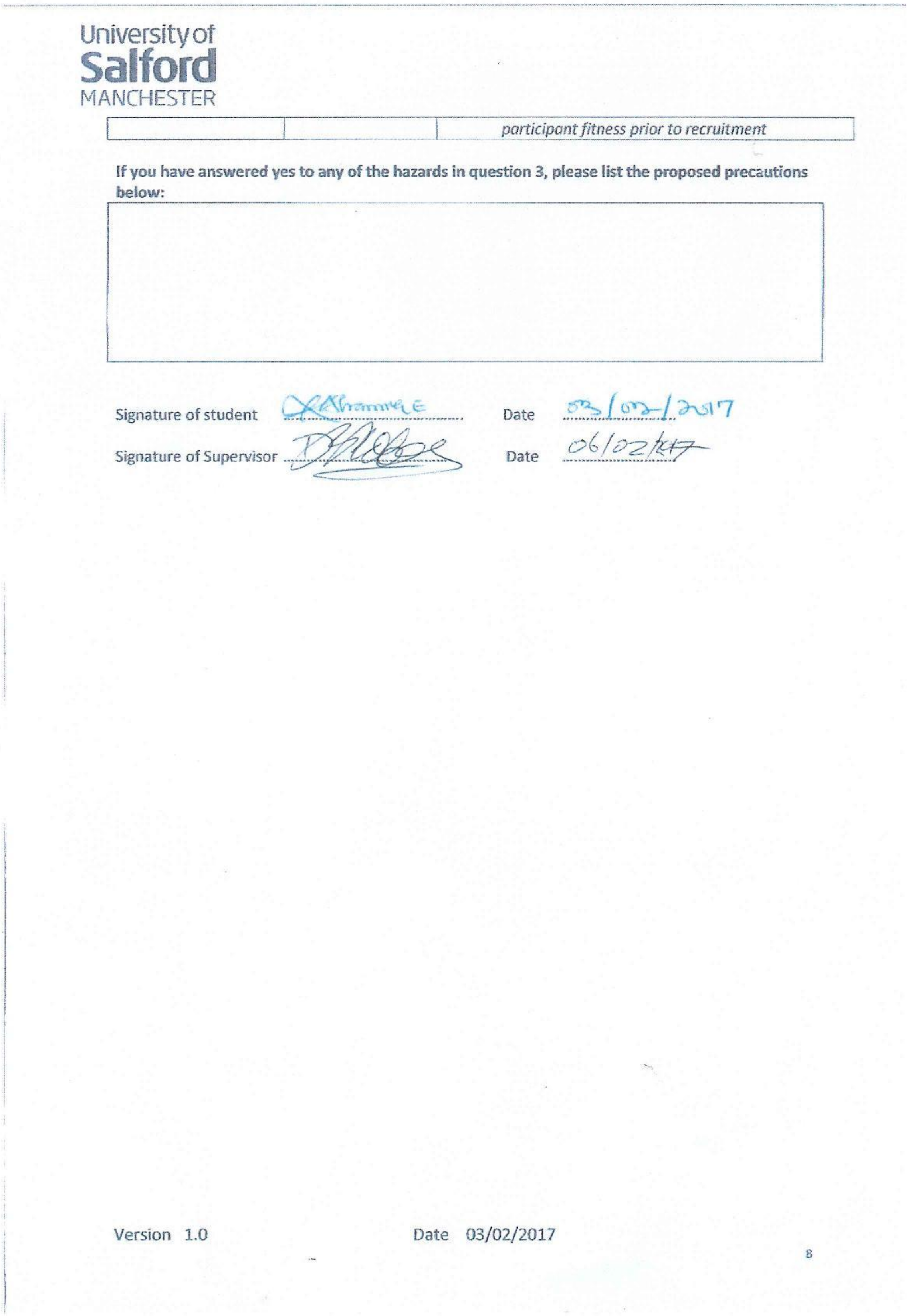
Use of face-to-face interviews *Participants or interviewees could become upset by interview and suffer psychological effects*	***No***	***Consider:*** - *What initial and subsequent support will be made available for participants or interviewees?* - *What to do if researcher uncovers information regarding an illegal act?* - *What/who will be used to counsel distressed participants/ interviewees, what precautions will be taken to prevent this from happening?*
Sensitive data	*Exposure to data or information which may cause upset or distress to Researcher* ***No***	***Consider:*** - *What initial and subsequent support will be available to the researcher*
Physical activity	*Exposure to levels of excerption unsuitable for a individuals level of fitness* ***No***	***Consider:*** - *Health Questionnaire/ Medical declaration form / GP clearance.* - *Trained First Aid personnel/ Equipment.*
Equipment	*Exposure to faulty unfamiliar equipment.* No	*Consider:* - *Equipment is regularly checked and maintained as manufactures instructions.* - *Operators receive adequate training in use of.* - *Participants receive induction training prior to use.*
Sensitive issues i.e. Gender / Cultural e.g. when observing or dealing with undressed members of the opposite sex	*Exposure to vulnerable situations/ sensitive issues that may cause distress to interviewer or interviewee* No	***Consider:*** - *Use of chaperones/ Translators.* - *What initial and subsequent support will be made available for participants or interviewees?*
Children	No	- *Adhere to local guidelines and take advice from research supervisor*
Manual Handling Activities	*Exposure to an activity that could result in injury* [✓ *No*]	- *Adapt the task to reduce or eliminate risk from manual handling activities. Ensure that participants understand and are capable of the manual handling task beforehand.* - *Perform health questionnaire to determine*



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		participant fitness prior to recruitment

If you have answered yes to any of the hazards in question 3, please list the proposed precautions below:

Signature of student .... Date 03/02/2017

Signature of Supervisor .... Date 06/02/2017

Version 1.0 Date 03/02/2017

APPENDIX 4: Godspeed Questionnaire

Appendix A: Overview of the Godspeed Questionnaire series using a 5-point scale.

GODSPEED I: ANTHROPOMORPHISM

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Fake 偽物のような	1	2	3	4	5	Natural 自然な
Machinelike 機械的	1	2	3	4	5	Humanlike 人間的
Unconscious 意識を持たない	1	2	3	4	5	Conscious 意識を持っている
Artificial 人工的	1	2	3	4	5	Lifelike 生物的
Moving rigidly ぎこちない動き	1	2	3	4	5	Moving elegantly洗練された動き

GODSPEED II: ANIMACY

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Dead 死んでいる	1	2	3	4	5	Alive 生きている
Stagnant 活気のない	1	2	3	4	5	Lively 生き生きとした
Mechanical 機械的な	1	2	3	4	5	Organic 有機的な
Artificial 人工的な	1	2	3	4	5	Lifelike 生物的な
Inert 不活発な	1	2	3	4	5	Interactive 対話的な
Apathetic 無関心な	1	2	3	4	5	Responsive 反応のある

GODSPEED III: LIKEABILITY

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Dislike 嫌い	1	2	3	4	5	Like 好き
Unfriendly 親しみにくい	1	2	3	4	5	Friendly 親しみやすい
Unkind 不親切な	1	2	3	4	5	Kind 親切な
Unpleasant 不愉快な	1	2	3	4	5	Pleasant 愉快な
Awful ひどい	1	2	3	4	5	Nice 良い

GODSPEED IV: PERCEIVED INTELLIGENCE

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Incompetent 無能な	1	2	3	4	5	Competent 有能な
Ignorant 無知な	1	2	3	4	5	Knowledgeable 物知りな
Irresponsible 無責任な	1	2	3	4	5	Responsible 責任のある
Unintelligent 知的でない,	1	2	3	4	5	Intelligent 知的な
Foolish 愚かな	1	2	3	4	5	Sensible 賢明な

GODSPEED V: PERCEIVED SAFETY

Please rate your emotional state on these scales:
以下のスケールに基づいてあなたの心の状態を評価してください。

Anxious 不安な	1	2	3	4	5	Relaxed 落ち着いた
Agitated 動揺している	1	2	3	4	5	Calm 冷静な
Quiescent 平穏な	1	2	3	4	5	Surprised 驚いた

APPENDIX 5: Salfordian Magazine Publication

[Above] *What the wearer sees in the VR headset*

REALITY BITES

Star Trek holodecks and gaming headsets are all in a day's work at Salford University's Virtual Reality hub, where students interact with Virtual Humans to aid research into how the human brain works.

The University of Salford has always been ahead of the curve when it comes to future innovation.

With the Oculus Rift virtual reality system kick-starting a growing market in virtual reality early in 2016, academics from various faculties noted the potential avenues VR could bring both students and academics from a research perspective.

As a number of researchers join the University as part of a growing VR group, student successes also demonstrate why Salford is seen as an epicentre of virtual innovation.

> "Salford is a great place to learn about VR, as it has a wide range of academic expertise and some of the best facilities in the world."

David Roberts, Professor of Telepresence at the University, says: "Salford is a great place to learn about VR as it has a wide range of academic expertise and some of the best facilities in the world. Not many other universities give undergraduate students access to multi-million pound VR research facilities."

In a recent interview, David discussed in more detail how the facilities at Salford could be safely used to maximum effect.

"A lot of my work is done in what we colloquially call 'caves' – which are a bit like the 'holodeck' in Star Trek," he said. "At the University of Salford, we have a cave called the Octave where you can project things all around you, - and can actually move around.

"Importantly you're not in there on your own – in one of these you could go in with a therapist, for example. Here, instead of being fully immersed, someone who is afraid of heights could be looking down into a VR hole, but with someone's hand on their hand on shoulder at the same time to reassure them."

While great efforts are being made to make the best use of the technology available in order to explore areas such as mental ▶

health, the University of Salford has long been regarded as a leader in areas of innovation.

In 1987 Salford was chosen as the UK's National Advanced Robotics Research Centre.

Since then Robotics has formed a major strategic direction within Engineering in the University of Salford where researchers have been at the forefront of national developments initiated by the Department of Trade and Industry (DTI), the Department for Environment, Food and Rural Affairs (DEFRA) and the Engineering and Physical Sciences Research Council (EPSRC) and international developments within the E.U, highlighting the University's forward-thinking innovation.

The success in the field of robotics saw further funding from the EPSRC to set up the National Industrial Centre for virtual reality in 1998.

As of 2017 Professor Roberts also works as a mentor for a small cohort of MSc and PhD students.

Here, he oversees the university's research into how people's brains are affected by a number of various stimuli in relation to anti-social behaviour, hangovers and addiction.

Professor Roberts continued: "It is useful to see how people respond to certain stimuli. VR allows stimuli, similar to that of the real world, to be controlled.

In more scientific terms it bridges the gap between ecological validity and controllability. VR looks as though it is set to be an everyday tool in mental health. Its use will soon need to be taught across mental health disciplines."

Psychology PhD student Godson Ahamba is one of four students currently using virtual reality to explore mental health.

"With real human beings our emotions and how we respond to people may vary based on other factors such as having a bad night," Godson explains.

"That would change the way we interacted but with a Virtual Human you can have it controlled and constant.

"That's a massive advantage of using VR and Virtual Humans as opposed to real humans who may be influenced by a variety of factors in that particular moment.

While there may be some way to go to complete virtual immersion, Godson says that he has gathered a variety of responses with some trialists demonstrating anger towards the provocative virtual human. This proves his initial belief through virtual provocation.

"There are actually no limits to what students can use Virtual Reality for I think."

Godson echoes the sentiments of his mentor when he speaks of the University's approach to research.

"It's massively important to have this kind of technology, because you always want to have an outlook to the future with every single research."

"This research may not be applied in the next one to two years, but it is likely to eventually lead research in this area.

"So what you are encouraged to do by staff is to look out for technologies that have the potential to stand-up in the future and not go back in time.

"Things are always changing and so it is really important not to cut out using technology these days because prior to this the use of technology has been scattered and detached.

"It is now at a point where we are trying to bring all these technological elements together and see what happens."

And bringing together the various elements of technology was helped, in part, to discussions with an industry professional at Sony, as talk turns to using Oculus Rift equipment, more often associated with gaming, for the purposes of research into a number of new areas.

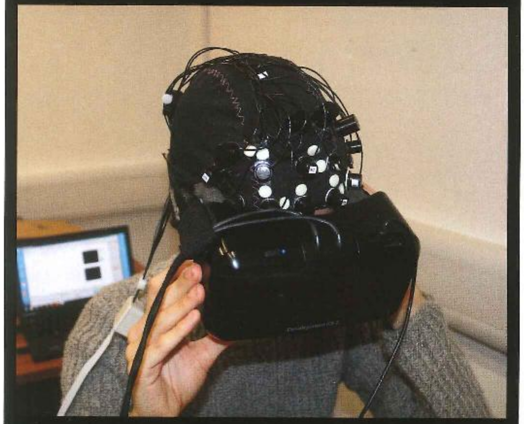
Godson believes that the collision of cutting-edge technology and innovative research has potential far beyond VR's current applications.

"Before now, the Oculus Rift for example, was never designed to be compatible with the brain-imaging cap.

But with this research we worked with someone from Sony and it became apparent that it is a very good idea for the headset to be used in research.

"Nobody had previously thought about wearing the head cap and the mounted display so by doing this all now the possibilities are endless."

HEAD GAMES



We undertook the University's virtual human experiment in a bid to better understand the impact Virtual Humans and virtual reality can have on academic research.

The brain-imaging cap we're wearing features a number of key sensors and detectors carefully calibrated to monitor our brain activity, along with a modified virtual reality headset. It looks like something from Doctor Who.

The experiment's topic centres around the 2017 General Election and Brexit discussions. Trialists engage in debate with two contrasting Virtual Humans: one polite, well-mannered gentleman and one far ruder and more abrupt.

Sitting down in a cosy office space on the top floor of the Allerton Building to take part in the study, the researchers explained that the experiment allows them to see how the brain responds to stimuli while they attempt to trigger an emotion in the brain.

While far from feeling complete immersion, a face-off with the two Virtual Humans was a different experience. Speaking back in dialogue with a non-existent human initially felt strange, knowing our responses were being directed to a wall, but the impression of partaking in a genuine conversation grew and grew as the experiment went on.

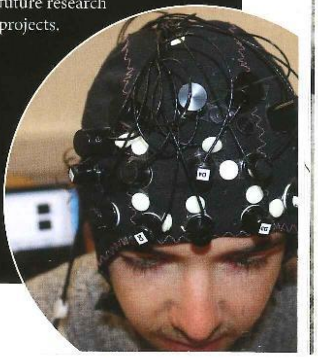
The provocative character – presented after the well-mannered gentleman – in particular triggers real emotion whereby participants are almost compelled to defend their political stance when they are shut down. Sharp and crude in his responses, the antithesis between the two Virtual Humans is stark.

What was telling – as is often the case with virtual reality – is that the cumbersome equipment is a sign that the platform still has quite a way to go before leading all of the future research.

The headset, specifically modified for research purposes, needs to become as natural to a person as a regular pair of glasses would.

And as for the feeling of leaving the virtual environment after an extended stint in the landscape, it took time for both our eyes and mind to readjust.

With an eye on the future, our time using virtual reality only reaffirms the belief that this is the benchmark for future research projects.



APPENDIX 6: Program Codes.

We only include the program for the button press animations of the two virtual humans. The codes are written in CSharp (A language developed by Microsoft within its .Net framework) which is supported by Unity3D.

Script for Calm Virtual Human

```
using UnityEngine;
using System.Collections;
using RogoDigital.Lipsync;

public class CalmVHScript : MonoBehaviour {

    Animator anim;
    LipSync lipsync;

    // Use this for initialization
    void Start () {
        anim = this.GetComponent<Animator>();
        lipsync = this.GetComponent<LipSync>();


    }

    // Update is called once per frame
    void Update () {
        /*Rest State starts*/
        if (Input.GetKeyDown("-"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/EnjoyedTalking") as LipSyncData, 1);


        }
        /*Rest State ends*/

        /*To get participants to continue talking*/
        if(Input.GetKeyDown("0"))
        {
            System.Random rnd = new System.Random();
            int rInt = rnd.Next(1, 2);

            if(rInt == 1)
            {
                lipsync.Play(Resources.Load("Final/LikePointofView") as LipSyncData, 1);
            }
```

```
            if(rInt == 2)
            {
               lipsync.Play(Resources.Load("Final/ThinkAlike") as LipSyncData, 1);
            }

        }
        /*To get participants to continue talking ends here*/

        /*First greeting and Intro*/
        if (Input.GetKeyDown("1"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as RuntimeAnimato
rController;
            //anim.runtimeAnimatorController = Resources.Load("Lincoln Example") as Runtime
AnimatorController;
            lipsync.Play(Resources.Load("Final/Intro") as LipSyncData, 0);
        }

        if (Input.GetKeyDown(KeyCode.F1))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/FineThankYou") as LipSyncData, 0);


        }
        /*To get participants to continue talking ends here*/

        /*Immigration neutral convo*/
        if (Input.GetKeyDown("2"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/EthnicDiversity") as LipSyncData, 0);
        }
        /*Immigration Neutral convo ends here*/

        /*Immigration support International students*/
        if (Input.GetKeyDown("3"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/IntlStudentsTuitionFees") as LipSyncData, 0);

        }
        /*Immigration support international students ends here*/

        if (Input.GetKeyDown(KeyCode.F3))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
```

```
Controller;
            lipsync.Play(Resources.Load("Final/Doyouthinkthatsfair") as LipSyncData, 0);


        }

        /*Immigration support Home students*/
        if (Input.GetKeyDown("4"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/UKleavingtheEU") as LipSyncData, 0);
        }
        /*Immigration support Home students ends here */

        if (Input.GetKeyDown("5"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/Brexit2") as LipSyncData, 0);
        }

        //Against Brexit
        if (Input.GetKeyDown("6"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/BritishPeopleLiedTo") as LipSyncData, 0);
        }

        if (Input.GetKeyDown("7"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/SecondReferendum") as LipSyncData, 0);
        }

        if (Input.GetKeyDown("8"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/ResearchFunding") as LipSyncData, 0);
        }

        if (Input.GetKeyDown("9"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/StayingTogether") as LipSyncData, 0);
        }
```

```
//Against Brexit Ends here

//In supportf of Brexit

if (Input.GetKeyDown("e"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/BrittonsHardtoGetJobs") as LipSyncData, 0);
}

if (Input.GetKeyDown("r"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/UKSpendsforEU") as LipSyncData, 0);
}

if (Input.GetKeyDown("t"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/ExpensiveBeingInEU") as LipSyncData, 0);
}

if (Input.GetKeyDown("y"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/LeavingEUManageFunds") as LipSyncData, 0);
}

if (Input.GetKeyDown("u"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/PartofAUnion") as LipSyncData, 0);
}

if (Input.GetKeyDown("f"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
    lipsync.Play(Resources.Load("Final/WhoIsBestToLead") as LipSyncData, 0);
}

if (Input.GetKeyDown("g"))
{
    //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
```

```
Controller;
            lipsync.Play(Resources.Load("Final/CorbynOrMay") as LipSyncData, 0);
        }

        if (Input.GetKeyDown("n"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/GreatInsight") as LipSyncData, 0);
        }

        if (Input.GetKeyDown("i"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/ElectionResult") as LipSyncData, 0);
        }
        if (Input.GetKeyDown("o"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/JeremyCorbynRunningCountry") as LipSyncDat
a, 0);
        }
        if (Input.GetKeyDown("p"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/TheresaMayResign") as LipSyncData, 0);
        }
        if (Input.GetKeyDown("h"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/NHS") as LipSyncData, 0);
        }
        if (Input.GetKeyDown("j"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/LabourNHSPlan") as LipSyncData, 0);
        }
        if (Input.GetKeyDown("k"))
        {
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimator
Controller;
            lipsync.Play(Resources.Load("Final/FateofBrexit") as LipSyncData, 0);
        }
        if (Input.GetKeyDown("l"))
        {
```

```
            //anim.runtimeAnimatorController = Resources.Load("Sittalk") as RuntimeAnimatorController;
            lipsync.Play(Resources.Load("Final/DUPAlliance") as LipSyncData, 0);
        }

        if (Input.GetKeyDown(KeyCode.F4))
        {

            anim.runtimeAnimatorController = Resources.Load("Anims/SitSimple") as RuntimeAnimatorController;

        }
        if (Input.GetKeyDown(KeyCode.F5))
        {

            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as RuntimeAnimatorController;

        }

    }
}
```

Script for Aggressive Virtual Human

```
using UnityEngine;
using System.Collections;
using RogoDigital.Lipsync;

public class AggressiveVHScript : MonoBehaviour {

   // Use this for initialization

   Animator anim;
   LipSync lipsync;

   void Start () {

      anim = this.GetComponent<Animator>();
      lipsync = this.GetComponent<LipSync>();
   }

         // Update is called once per frame
         void Update () {

      if (Input.GetKeyDown("0"))
      {
         //transform.position = new Vector3(-5 , 0, -5);
         anim.runtimeAnimatorController        =        Resources.Load("Anims/Anim2")        as
RuntimeAnimatorController;
         lipsync.Play(Resources.Load("B1/UtterRubbish") as LipSyncData, 0);
      }

      if (Input.GetKeyDown("1"))
      {
         anim.runtimeAnimatorController          =          Resources.Load("Anims/Sit")          as
RuntimeAnimatorController;
         lipsync.Play(Resources.Load("B1/Intro") as LipSyncData, 0);
      }



      if (Input.GetKeyDown("2"))
      {
         anim.runtimeAnimatorController          =          Resources.Load("Anims/Sit")          as
RuntimeAnimatorController;
         lipsync.Play(Resources.Load("B1/Brexit") as LipSyncData, 0);
      }

      if (Input.GetKeyDown(KeyCode.F2))
      {
         anim.runtimeAnimatorController        =        Resources.Load("Anims/Anim2")        as
RuntimeAnimatorController;
```

```
            lipsync.Play(Resources.Load("B1/Immigration") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("3"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/NegotiatingPower") as LipSyncData, 0);

        }

        //Support Brexit

        if (Input.GetKeyDown("4"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/GeneralElectionsResult") as LipSyncData, 0);

        }


        //Oppose Brexit

        if (Input.GetKeyDown("5"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/MayResignCorbyn") as LipSyncData, 0);

        }


        if (Input.GetKeyDown("6"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/MayResign") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("7"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/CorbynOrMay") as LipSyncData, 0);

        }
```

```
        if (Input.GetKeyDown("8"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/WhyCorbyn") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("9"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Sit") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/WhyMay") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("-"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/EndingConversation2") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("="))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/NeedAnswer") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("n"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/NoIdea") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("m"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as
RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/Nonsense") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("f"))
        {
```

```
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/HardorSoftBrexit") as LipSyncData, 0);

        }

        if (Input.GetKeyDown("g"))
        {
            anim.runtimeAnimatorController = Resources.Load("Anims/Anim2") as RuntimeAnimatorController;
            lipsync.Play(Resources.Load("B1/NHS") as LipSyncData, 0);

        }



    }
}
```

APPENDIX 7: Correlation result.

Correlation of ROI1 (Condition 1) and Latency for part 1 of Hayling Task

Correlations

		ROI1	H1
ROI1	Pearson Correlation	1	-.332
	Sig. (2-tailed)		.165
	N	19	19
H1	Pearson Correlation	-.332	1
	Sig. (2-tailed)	.165	
	N	19	19

Correlation of ROI1 (Condition 1) and Latency for part 2 of Hayling Task

Correlations

		ROI1	H2
ROI1	Pearson Correlation	1	-.394
	Sig. (2-tailed)		.095
	N	19	19
H2	Pearson Correlation	-.394	1
	Sig. (2-tailed)	.095	
	N	19	19

Correlation of ROI2 (Condition 1) and Latency for part 1 of Hayling Task

Correlations

		ROI2	H1
ROI2	Pearson Correlation	1	-.223
	Sig. (2-tailed)		.358
	N	19	19
H1	Pearson Correlation	-.223	1

	Sig. (2-tailed)	.358	
	N	19	19

Correlation of ROI2 (Condition 1) and Latency for part 2 of Hayling Task

Correlations

		ROI2	H2
ROI2	Pearson Correlation	1	.075
	Sig. (2-tailed)		.761
	N	19	19
H2	Pearson Correlation	.075	1
	Sig. (2-tailed)	.761	
	N	19	19

Correlation of ROI3 (Condition 1) and Latency for part 1 of Hayling Task

Correlations

		ROI3	H1
ROI3	Pearson Correlation	1	-.191
	Sig. (2-tailed)		.434
	N	19	19
H1	Pearson Correlation	-.191	1
	Sig. (2-tailed)	.434	
	N	19	19

Correlation of ROI3 (Condition 1) and Latency for part 2 of Hayling Task

Correlations

		ROI3	H2
ROI3	Pearson Correlation	1	.088
	Sig. (2-tailed)		.720
	N	19	19

H2	Pearson Correlation	.088	1
	Sig. (2-tailed)	.720	
	N	19	19

Correlation of ROI4 (Condition 1) and Latency for part 1 of Hayling Task

Correlations

		ROI4	H1
ROI4	Pearson Correlation	1	.052
	Sig. (2-tailed)		.833
	N	19	19
H1	Pearson Correlation	.052	1
	Sig. (2-tailed)	.833	
	N	19	19

Correlation of ROI4 (Condition 1) and Latency for part 2 of Hayling Task

Correlations

		ROI4	H2
ROI4	Pearson Correlation	1	.099
	Sig. (2-tailed)		.687
	N	19	19
H2	Pearson Correlation	.099	1
	Sig. (2-tailed)	.687	
	N	19	19

Correlation of ROI1 (Condition 2) and Latency for part 1 of Hayling Task

Correlations

		ROI1_2	H1
ROI1_2	Pearson Correlation	1	-.077
	Sig. (2-tailed)		.755
	N	19	19

H1	Pearson Correlation	-.077	1
	Sig. (2-tailed)	.755	
	N	19	19

Correlation of ROI1 (Condition 2) and Latency for part 2 of Hayling Task

Correlations

		ROI1_2	H2
ROI1_2	Pearson Correlation	1	.484*
	Sig. (2-tailed)		.036
	N	19	19
H2	Pearson Correlation	.484*	1
	Sig. (2-tailed)	.036	
	N	19	19

*. Correlation is significant at the 0.05 level (2-tailed).

Correlation of ROI2(Condition 2) and Latency for part 1 of Hayling Task

Correlations

		ROI2_2	H1
ROI2_2	Pearson Correlation	1	.088
	Sig. (2-tailed)		.721
	N	19	19
H1	Pearson Correlation	.088	1
	Sig. (2-tailed)	.721	
	N	19	19

Correlation of ROI2 (Condition 2) and Latency for part 2 of Hayling Task

Correlations

		ROI2_2	H2
ROI2_2	Pearson Correlation	1	.353
	Sig. (2-tailed)		.138
	N	19	19

H2	Pearson Correlation	.353	1
	Sig. (2-tailed)	.138	
	N	19	19

Correlation of ROI3 (Condition 2) and Latency for part 1 of Hayling Task

Correlations

		ROI3_2	H1
ROI3_2	Pearson Correlation	1	.113
	Sig. (2-tailed)		.644
	N	19	19
H1	Pearson Correlation	.113	1
	Sig. (2-tailed)	.644	
	N	19	19

Correlation of ROI3 (Condition 2) and Latency for part 2 of Hayling Task

Correlations

		ROI3_2	H2
ROI3_2	Pearson Correlation	1	.258
	Sig. (2-tailed)		.286
	N	19	19
H2	Pearson Correlation	.258	1
	Sig. (2-tailed)	.286	
	N	19	19

Correlation of ROI4 (Condition 2) and Latency for part 1 of Hayling Task

Correlations

		ROI4_2	H1
ROI4_2	Pearson Correlation	1	-.414
	Sig. (2-tailed)		.078
	N	19	19
H1	Pearson Correlation	-.414	1

	Sig. (2-tailed)	.078	
	N	19	19

Correlation of ROI4 (Condition 2) and Latency for part 1 of Hayling Task

Correlations

		ROI4_2	H2
ROI4_2	Pearson Correlation	1	.056
	Sig. (2-tailed)		.821
	N	19	19
H2	Pearson Correlation	.056	1
	Sig. (2-tailed)	.821	
	N	19	19

APPENDIX 8: MANOVA Result

MANOVA test for Hayling task and conversation task using condition (friendly and unfriendly represented by 1 and 2 respectively) as independent variable experiment (Hayling task and experimental task also represented by 1 and 2 respectively) as covariate variable.

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	LDLPFC	1.209E-5[a]	3	4.031E-6	2.002	.131
	RDLPFC	5.184E-6[b]	3	1.728E-6	1.135	.348
	LMPFC	1.214E-5[c]	3	4.047E-6	.533	.662
	RMPFC	.001[d]	3	.000	.934	.434
Intercept	LDLPFC	2.483E-6	1	2.483E-6	1.233	.274
	RDLPFC	4.000E-7	1	4.000E-7	.263	.611
	LMPFC	9.877E-7	1	9.877E-7	.130	.720
	RMPFC	.000	1	.000	.820	.371
Condition	LDLPFC	5.232E-6	1	5.232E-6	2.599	.116
	RDLPFC	9.749E-7	1	9.749E-7	.640	.429
	LMPFC	8.249E-6	1	8.249E-6	1.087	.304
	RMPFC	.000	1	.000	.908	.347
Experiment	LDLPFC	3.755E-6	1	3.755E-6	1.865	.180
	RDLPFC	3.643E-6	1	3.643E-6	2.392	.131
	LMPFC	3.011E-6	1	3.011E-6	.397	.533
	RMPFC	.000	1	.000	.940	.339
Condition * Experiment	LDLPFC	3.105E-6	1	3.105E-6	1.543	.222
	RDLPFC	5.666E-7	1	5.666E-7	.372	.546
	LMPFC	8.811E-7	1	8.811E-7	.116	.735
	RMPFC	.000	1	.000	.953	.335
Error	LDLPFC	7.247E-5	36	2.013E-6		
	RDLPFC	5.482E-5	36	1.523E-6		
	LMPFC	.000	36	7.586E-6		
	RMPFC	.010	36	.000		
Total	LDLPFC	8.705E-5	40			
	RDLPFC	6.040E-5	40			
	LMPFC	.000	40			
	RMPFC	.011	40			
Corrected Total	LDLPFC	8.456E-5	39			
	RDLPFC	6.000E-5	39			

	LMPFC	.000	39			
	RMPFC	.011	39			

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df
Intercept	Pillai's Trace	.110	1.021[b]	4.000	33.000
	Wilks' Lambda	.890	1.021[b]	4.000	33.000
	Hotelling's Trace	.124	1.021[b]	4.000	33.000
	Roy's Largest Root	.124	1.021[b]	4.000	33.000
Condition	Pillai's Trace	.121	1.134[b]	4.000	33.000
	Wilks' Lambda	.879	1.134[b]	4.000	33.000
	Hotelling's Trace	.137	1.134[b]	4.000	33.000
	Roy's Largest Root	.137	1.134[b]	4.000	33.000
Experiment	Pillai's Trace	.105	.969[b]	4.000	33.000
	Wilks' Lambda	.895	.969[b]	4.000	33.000
	Hotelling's Trace	.117	.969[b]	4.000	33.000
	Roy's Largest Root	.117	.969[b]	4.000	33.000
Condition * Experiment	Pillai's Trace	.093	.843[b]	4.000	33.000
	Wilks' Lambda	.907	.843[b]	4.000	33.000
	Hotelling's Trace	.102	.843[b]	4.000	33.000
	Roy's Largest Root	.102	.843[b]	4.000	33.000

a. Design: Intercept + Condition + Experiment + Condition * Experiment

b. Exact statistic

APPENDIX 9: t-test result of our ROIs, Study 1

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	ROI1 - TROI1	-.000304	.000596	.000188	-.000730	.000122	-1.613	9	.141
Pair 2	ROI2 - TROI2	-.000330	.000386	.000122	-.000606	-.000054	-2.701	9	.024
Pair 3	ROI3 - TROI3	-.000432	.000426	.000135	-.000736	-.000127	-3.208	9	.011
Pair 4	ROI4 - TROI4	-.000486	.000391	.000124	-.000765	-.000206	-3.932	9	.003

APPENDIX 10: Conversation Scripts

Here we capture the conversation scripts for each of the virtual human confederates. Please not that the conversations are controlled by button presses (Appendix 6).

Conversation script for friendly virtual human confederate:

- Hi, my name is Chris, it's nice having you here. How are you?
- I'm fine, thanks for asking
- We've got much more ethnic diversity in the UK these days, what's your take on it, and what's your take on the laws
- Did you know that international students have to pay far more for their tuition fees? Do you think that's fair?
- It's been about a year since the UK decided to leave the EU, what's your take on Brexit
- Given that some people say the British people were lied to in the referendum, should we really be moving forward to Brexit?
- Should we have a second referendum to make sure the British people have all the information in front of them before making such a big decision?
- What about research funding
- Who is best to lead us in the Brexit negotiations? Corby or May?
- What is the fate of Brexit given the election result?
- What do you think about the alliance with the DUP?
- What do you think about the NHS?
- Do you think labour has a better plan for the NHS?
- That's great insight
- I like your point of view

Conversation script for unfriendly virtual human confederate:

- You were supposed to be here a little while ago, it's really rude to be late and not even apologise. Well I suppose we just get this started and see if we can get some useful data from this conversation.
- So what's your position on Brexit
- Okay, well if you're so against Brexit, what are we going to do about immigration.

- Okay, well if you’re so pro-Brexit, what are we going to do about the economy, surely you can’t think that a single country has the same negotiating power as a whole block.
- So what do you think about the result of the general election then
- So after the results of this election, do you think Theresa May should resign? Surely you don’t want to government to Jeremy Corbyn
- So given the results of this needless election, don’t you think Theresa May should resign
- Okay that’s enough party politics, let’s move on to just the leaders, let’s get your opinion on Jeremy Corbyn and Theresa May
- Why would you support Jeremy Corbyn? He’s weak on security, he can’t protect us.
- Why would you support Theresa May? I mean she claims to be strong and stable, but all she does is u-turn on things, I mean take this general elections for example.
- So given the result sof the election, which way do you think we are going to go? Hard or soft Brexit?
- What about the NHS? Surely you can’t see that as safe and secure under this coalition of chaos.
- You know what? If you ask me, that’s just utter rubbish.
- You know what? That’s just nonsense, I can’t believe somebody would think like that.
- I have no idea what you mean, makes no sense to me at all.

APPENDIX 11: Hayling Task

- The University of ________
- As white as _________
- A good looking _________
- As black as ____________
- As deep as ___________
- I need to visit a ____________
- I feel ___________
- It is important to eat on a daily ___________
- My house is __________
- I am ___________
- The man appears to be ____________
- I dislike ____________
- It is dangerous to play with ____________
- A beautiful ____________
- An interesting movie is showing at the ___________