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Exploring Social Anxiety in Digital Platforms within Novel Experimental Laboratory Paradigms

by

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Abstract

Social anxiety disorder (SAD) is a prevalent and persistent condition that has a significant impact on an individual's quality of life. It is important to understand the mechanisms that contribute to the development of SAD, in order to develop more effective and evidence-based treatments. The central objective of this thesis is to develop experimental paradigms that can simulate social anxiety in online and virtual platforms in human participants, and to test their potential in understanding the underlying mechanisms of SAD. The thesis first provides an overview of the nature and prevalence of social anxiety and reviews the literature on changes in social anxiety diagnostic criteria. It then critically evaluates influential social anxiety theories alongside empirical evidence. Subsequently, it investigates the experimental human models of anxiety induced by both psychological and biological challenges. Lastly, the thesis discusses the role of technology in social anxiety research, particularly focusing on virtual and online platforms, and presents three empirical studies. The first study examines the combination of a socially evaluative public speaking task in virtual reality (VR) and CO_2 gas mixture as a potential paradigm for inducing anxiety in healthy individuals, with a focus on its relevance to cognitive mechanisms of SAD. The findings revealed that the augmentation of the CO_2 gas and a virtual public speaking task resulted in heightened subjective and objective arousal. In addition, participants who performed within this augmentation had more severe anticipatory processing (measured retrospectively) and underestimated their performance. The second study investigates the anxiogenic effects of a photorealistic 360-degree public speaking VR scenario as a potential laboratory human model of anxiety, and its relevance to trait and situational social anxiety. Further, this study explores the potential habituation effects that might occur as a result of performing in the virtual task, within a subsequent real-life socially evaluative scenario (calculation task). We found meaningful effects that this paradigm can induce situational social anxiety. We also discovered some trends on the relevance of our paradigm to trait social anxiety. The final study explores how the camera features of online communication platforms support the validity of social anxiety theories, which have gained popularity, especially since the COVID-19 pandemic outbreak. The findings provided evidence that our online protocol could be utilised as an anxiogenic paradigm. Furthermore, our findings revealed that when participants performed in front of an audience with audience images/videos turned off, but with their own self-depicting video on, they rated their performance more poorly and engaged in more frequent post-event processing. These results provide additional support for the validity of existing theories regarding social anxiety in online communication platforms. Overall, the thesis contributes to a better understanding of the underlying mechanisms involved in SAD in virtual and online socially evaluative paradigms and can provide valuable insights for developing effective treatment approaches.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
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6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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Definitions and Abbreviations

ANCOVA .... Analysis of Covariance

ANOVA .... Analysis of Variance

AI .... Artificial Intelligence

AP .... Anticipatory Processing

APA .... American Psychiatric Association

ASI .... Anxiety Sensitivity Index

BP .... Blood Pressure

CBT .... Cognitive Behavioural Therapy

CCC................................ Concordance Class Correlation

CCTV.............................. Closed-circuit television

COVID-19 .... Coronavirus Disease

CPT .... Cold Pressor Task

CO_2................................ Carbon Dioxide

DSM .... The Diagnostic and Statistical Manual of Mental Disorders

ECG................................ Electrocardiogram

GAD................................ Generalised Anxiety Disorder

GAD-7 .... Generalised Anxiety Disorder Assessment

HPA .... Hypothalamic–Pituitary–Adrenal Axis

HR .... Heart Rate

ICC .... Intraclass Correlation Coefficient

iTSST .... Internet-delivered Trier Social Stress Test

NICE............................... National Institute for Health and Care Excellence

PEP .... Post-event Processing

PPG................................ Photoplethysmography

PQ .... Presence Questionnaire

PSI .... Panic Symptom Inventory

PANAS .... Positive and Negative Affect Scale

PST .... Public Speaking Task

SAD .... Social Anxiety Disorder

SASCI .... Social Anxiety Session Change Index

SET .... Socially Evaluative Threat

SFA .... Self-focused Attention

SNS................................ Sympathetic Nervous System

SPS .... Speech Performance Scale

SPST............................... Simulated Public Speaking Test

SSRI................................ Selective Serotonin Reuptake Inhibitor

SUDS .... Subjective Units of Distress

TQ .... Thoughts Questionnaire

TSST .... the Trier Social Stress Test

VAS .... Visual Analogue Scale

VR .... Virtual Reality

VRET .... Virtual Reality Exposure Therapy

WSAP .... Word Sentence Association Paradigm

Chapter 1 – Exploring Social Anxiety in Digital Platforms within Novel Experimental Laboratory Paradigms

1.1. Chapter Overview

Social Anxiety Disorder (SAD) is a debilitating condition that can significantly impact the daily life functioning of individuals. Psychological models have identified several mechanisms that contribute to the maintenance of SAD. Leveraging technological advancements, researchers have developed anxiogenic paradigms to better understand social anxiety and evaluate new therapeutic interventions. This chapter provides a comprehensive review of social anxiety and its associated cognitive mechanisms. It then summarises the experimental protocols that elicit anxiety that have been tested on healthy people, in order to gain insights into the underlying cognitive mechanisms of anxiety disorders. This chapter also discusses anxiogenic protocols and studies their relevance to social anxiety in socially evaluative/threatening situations.

1.2. Social Anxiety: Nature, Prognosis and Treatment

The present definition of SAD extends back nearly six decades, when Marks and Gelder (1966) first documented it as a condition in which a person suffers intense anxiety when subjected to inspection by others. Only with the publication of the Diagnostic and Statistical Manual of Mental Disorders 3 (DSM-3) (American Psychiatric Association, 1980), social anxiety was formally recognised as a distinct clinical diagnosis under the name of social phobia (Liebowitz et al., 1985). In the fifth and the most current form of the DSM (American Psychiatric Association, 2013), SAD has been listed under anxiety disorders, and is defined by a persistent and marked fear/anxiety about one or more social or performance situations in social settings (see Table 1 for the diagnostic criteria). The core feature in SAD is a fear of potential negative evaluations from others during social encounters that people with social anxiety believe will likely result in rejection, embarrassment or humiliation (Heimberg, Hofmann, et al., 2014).

Epidemiological studies have indicated that SAD is one of the most commonly reported psychiatric disorder after major depressive disorder (Kessler et al., 2005; Kessler et al., 2012). SAD has an estimated lifetime prevalence of 4% across the world (Stein et al., 2017), and 7% to 13% in Europe (Fehm et al., 2005), with higher prevalence rates in developed countries (Remes et al., 2016; Stein et al., 2010).

SAD typically emerges during mid-adolescence, and the highest incidence rates occur between the ages of 10 and 20 (Beesdo et al., 2007; Fehm et al., 2008). If left untreated, social anxiety symptomology often develops into a chronic condition (Yonkers et al., 2003), that is likely to persist into adulthood (Steinert et al., 2013). The naturalistic prognosis is also observed to be more severe among people with social anxiety compared to those with other anxiety disorders. According to a naturalistic observational study

Table 1

DSM-5 Criteria for Social Anxiety Disorder

Diagnostic Criteria	*Class: Anxiety Disorders*
A. Marked fear or anxiety about one or more social situations in which the individual is exposed to possible scrutiny by others. Examples include social interactions (e.g., having a conversation or meeting new people), being observed while performing routine tasks (e.g., eating or drinking), or performing in front of others (e.g., giving a speech).	
B. Persistent fear of acting in a way or show anxiety symptoms that will be negatively evaluated (i.e., will be humiliating or embarrassing; will lead to rejection or offend others).	
C. The social situations almost always provoke fear or anxiety.	
D. The social situations are avoided or endured with intense fear or anxiety.	
E. The fear or anxiety is out of proportion to the actual threat posed by the social situation and to the sociocultural context.	
Specify if:	
Performance only: When the fear is restricted to speaking or performing in public.	

*Note***.** To be diagnosed, criteria A-E must cause considerable distress or interfere with everyday functioning for at least six months, not be linked to any physiological conditions, and not be attributed to any other mental health disorder.

spanning 12 years, Bruce et al. (2005) reported that SAD had a recovery rate of only 37%, while those with generalised anxiety and panic disorder had recovery rates of 58% and 82%, respectively.

According to Davila and Beck (2002), individuals with social anxiety exhibit distinct patterns in their interpersonal relationships, such as reduced expression of emotions and more fear of rejection, which could potentially impede the formation of close relationships. Additionally, the significant levels of anxiety experienced by people with social anxiety might have severe impacts on their daily functioning in occupational domains. Long-term disability was found to be most prevalent for SAD relative to other anxiety disorders (Hendriks et al., 2016). The average number of workdays missed due to SAD was recorded to be 24.7 annually (Stein et al., 2017), implying that SAD may impose a substantial economic burden on society (Trautmann et al., 2016).

In addition, individuals diagnosed with social anxiety have a high likelihood of developing additional psychiatric conditions, with lifetime comorbidity rates of up to 80% (Stein et al., 2017), highlighting the importance of addressing comorbidity in treating SAD and enhancing outcomes for patients with the disorder (Koyuncu et al., 2019).

1.2.1. Social Anxiety Subtypes

The practice of identifying and categorising symptoms to diagnose anxiety disorders has primarily arisen from the need for clinical accuracy. Subtyping SAD has been a central concern since its inclusion in DSM-3 (American Psychiatric Association, 1980), due to the wide range of fears people experience in social situations (see Dalrymple and D'Avanzato (2013) for a summary). To recognise this heterogeneous symptomology, the DSM-3-R (American Psychiatric Association, 1987) introduced a 'generalised' subtype to account for cases where fear of an individual applies to most social situations, but the lack of specificity in the number or type of feared social situations led to researchers adapting their own operational definitions for subtyping SAD.

In a categorical approach to subtyping SAD, Heimberg et al. (1993) differentiated the 'generalised' subtype from other subtypes of SAD (e.g., non-generalised, circumscribed), focusing on the *number* of feared social situations. In generalised SAD, individuals would experience clinically significant anxiety in most social situations and social interactions. On the other hand, in non-generalised SAD, individuals may experience anxiety in specific social situations or settings but not in others. For example, an individual with non-generalised SAD may feel comfortable interacting with friends or family members but may experience anxiety in public speaking situations, or in large groups of unfamiliar people. This subtype of SAD is often referred to as 'circumscribed', because the anxiety is limited to certain specific social situations. Hofmann and Roth (1996) and Hofmann et al. (1999) also used a categorical approach to subtyping SAD, but with a slightly different interpretation of the 'generalised' subtype. In their studies, individuals who feared at least four common social situations received a diagnosis of the generalised social phobia subtype.

In addition to a quantitative approach, some researchers have suggested a qualitative classification for subtyping SAD, based on the *type* of feared social situations. Turner et al. (1992) and Stemberger et al. (1995) proposed a clinical classification system that identified a 'generalised' subtype of SAD if the anxiety was related only to social interactions, such as attending social events or engaging in conversations. For other feared situations that did not involve direct social interaction, such as public speaking or eating in public, individuals were assigned to a 'specific' subtype, regardless of the number of feared situations.

Recently, researchers have attempted to identify classes of similar social situations to reflect the heterogeneity in the expression of SAD. While the theoretical literature mostly supports two types of feared social settings (i.e., social interaction anxiety and performance-related social anxiety (Mattick & Clarke, 1998)), confirmatory factor analyses often fail to fit the data, as seen in studies (Safren et al., 1999; Safren et al., 1998; Sakurai et al., 2005). The results from exploratory factor analyses have also been inconsistent due to the diverse study methodologies used, including questionnaires and sample characteristics. For example, there was evidence of a three-factor solution (i.e., interaction anxiety, anxiety about being observed by others, fear that others will notice anxiety symptoms (Safren et al., 1998)), a four-factor solution (i.e., social interaction, public speaking, observation by others, eating and drinking in public (Safren et al., 1999), and even a five-factor solution (interpersonal anxiety, formal speaking anxiety, stranger-authority anxiety, eating and drinking while being observed, anxiety of doing something while being observed (Perugi et al., 2008)).

The results of studies examining subtyping of SAD have produced mixed findings when comparing community and clinical samples. Stein et al. (2000) and Vriends et al. (2007) found no clear subtyping classifications in community samples, while Eng et al. (2000) identified a three-factor subtype of SAD in a large clinical sample. Furthermore, Heimberg, Hofmann, et al. (2014) noted that certain anxiolytic drugs may be effective in treating patients with performance-only social fears, but not in those with other subtypes of SAD.

In recognising the discussions above, the fifth and latest version of the DSM (American Psychiatric Association, 2013) included a performance specifier to differentiate individuals who fear only performance situations from those with multiple fears. This new subtype replaces the generalised specifier, and is based on prior work that has shown differences between individuals with performance-only fears and those with multiple fears (Bögels et al., 2010). The fear of negative evaluation is a key feature of this subtype as well, as it is centred around the fear of failing or performing poorly in performance situations, leading to intense anxiety in affected individuals.

Despite the efforts to subtype SAD, the topic remains controversial, and there has been a recent push towards a more personalised and contextualised approach. Recent initiatives encourage this approach, such as the Research Domain Criteria (RDoC) (Insel, 2014), aimed at understanding the central features of psychopathology (e.g., threat appraisals) that can span across multiple diagnostic categories (Hyett & McEvoy, 2018). Such a perspective would help to better understand the varied presentations of SAD (Hofmann et al., 2004) and guide treatment planning, rather than trying to fit individuals into a limited set of categories (Aderka et al., 2012; Bögels et al., 2010; D’Avanzato & Dalrymple, 2016; Stein et al., 2010).

1.2.2. Treatment Approaches to Social Anxiety

Various assessment tools are available for assessing social anxiety, including self-report questionnaires and diagnostic interviews in clinical settings. The choice of assessment instrument is typically determined by the objectives of the study and the characteristics of the population under investigation (Wong et al., 2016).

Both psychological and pharmacological interventions have been shown effectively to reduce symptom severity in SAD (National Institute for Health and Care Excellence, 2013; Pelissolo et al., 2019). The pharmacological treatments mostly involve prescribing selective serotonin reuptake inhibitors (SSRIs) as treatment choice (Williams et al., 2020). Patient response to the different SSRI medications, however, varied due to different side effects increasing dropout rates (Del Re et al., 2013). Psychological interventions, specifically cognitive behavioural therapy (CBT), are the current recommended first-line treatment due to their effectiveness (Andrews et al., 2018; Pilling et al., 2013) and lack of side effects, as opposed to pharmacological interventions (Mayo-Wilson et al., 2014). CBT interventions for social anxiety are grounded in theoretical models ((Clark & Wells, 1995; Heimberg et al., 2010); see Hofmann (2007) for a comprehensive account on treatment implications), with a variety of techniques aimed at addressing different aspects of the disorder. These include education about social anxiety, exposure therapy that gradually exposes individuals to the social situations they fear, experiential interventions that illustrate the negative impact of cognitive biases, emotion regulation strategies, video feedback to correct distorted self-images, cognitive restructuring, and relapse prevention (Heimberg, 2002). Within the psychological treatment options, recent meta-analyses have reported medium to large effects associated with CBT for anxiety disorders, with superior effectiveness of CBT in reducing social anxiety symptom severity during one to six months of follow-up (Hedges *g*, 0.60; 95% CI, 0.36-0.85) compared to other interventions, including psychoeducation, supportive therapy, relaxation, pill placebo, care as usual, or waiting list. However, these observed effects of CBT decreased considerably at six to 12 months of follow-up (Hedges' g, 0.34; 95% CI, 0.07-0.61) (van Dis et al., 2020).

Technological advancements have brought about new ways of providing psychological interventions that can be delivered over the internet (Andrews et al., 2015), or in virtual worlds that offer realistic, three-dimensional simulations of real-life experiences (Emmelkamp et al., 2020). Both online (Kampmann et al., 2016) and virtual platforms (Garcia-Palacios et al., 2007; Keller et al., 2017) are empirically proven to be beneficial for the treatment of anxiety disorders as traditional face-to-face methods. Internet-delivered CBT has met the criteria of American Psychiatric Association (APA) for an empirically supported treatment for SAD, with large effect sizes across the anxiety disorders (Cohen's d = 1.13, 95 % CI = .99–1.28) (Hedman et al., 2012). Internet-delivered CBT is shown to be more effective than waiting list and active control interventions (Mewton et al., 2014), and has comparable efficacy to face-to-face interventions in reducing symptom severity (Andrews et al., 2010). Likewise, investigations into whether using immersive virtual environments is an effective medium to deliver CBT, in particular exposure therapy, have increased significantly (Freeman et al., 2017). Recent evidence indicates that VR might be as effective as face-to-face exposure therapy (Carl et al., 2019; Kampmann et al., 2016), and has the potential to address gaps in traditional exposure therapy, such as reducing the stigma associated with seeking treatment and increasing accessibility to treatment (Maples-Keller et al., 2017).

1.2.3. Summary: Social Anxiety Nature, Prognosis and Treatment

To summarise, social anxiety is a common disorder with an onset typically occurring in adolescence. Without proper treatment, the disorder can persist into adulthood, impeding daily functioning and interpersonal relationships. Comorbidities with other psychiatric disorders are also prevalent in individuals with SAD. Subtyping social anxiety has been a central concern, with different researchers proposing different categorical and qualitative approaches based on the type, number, and severity of the feared social situations. CBT has been recommended as the first-line treatment for SAD due to its effectiveness and lack of side effects. While traditional, face-to-face CBT has been shown to be effective, its long-term benefits may require additional treatment or customised interventions. Psychological interventions including CBT can be delivered through online and virtual platforms with comparable efficacy to face-to-face interventions.

1.3. Theories and Biases in Social Anxiety Disorder

Anxiety is a complex psychological phenomenon that can be conceptualised as an adaptive response and also as a pathological condition with high levels of disability (Gutiérrez-García & Contreras, 2013). The human survival mechanism is activated when we are faced with a threat, leading to a reaction that enables us to cope with potential dangers. In cases of adaptive anxiety, such reactions typically diminish once the threat is no longer present (Eysenck, 2013). From a pathological perspective, people with anxiety-related disorders exhibit distinct cognitive, behavioural, and emotional processing of these threatening stimuli, which persist beyond the removal of the threat itself. These responses are evident prior to, during, and following exposure to the perceived threat, and this contributes to the chronicity of the disorder (Bar-Haim et al., 2007).

In the cognitive literature on social anxiety, threat processing has been classified into four different types of biases (Morrison & Heimberg, 2013). First, attentional bias refers to the propensity of socially anxious people to attend selectively to internal or external cues that are related to potential threats (Bar-Haim et al., 2007; Bögels & Mansell, 2004). Second, interpretation bias involves the inclination to attribute negative meanings to ambiguous stimuli (Amir, Beard, & Bower, 2005; Huppert et al., 2003). Third, judgment bias pertains to the underestimation of one's capacity to regulate external threats, as well as an overestimation of the negative consequences of social events (Hofmann, 2007). Lastly, memory bias is characterised by the tendency of individuals to recall past social experiences as more negative or threatening than they actually were (Hackmann et al., 2000; Kuckertz & Amir, 2014). Cognitive models of social anxiety suggest that these biases are interconnected to each other, exacerbating the symptomology and further maintaining the disorder (Hirsch et al., 2006; Schultz &

Heimberg, 2008). These biases have their roots in the cognitive theories of social anxiety, which have shaped the trajectory of empirical research in this area (Clark & Wells, 1995; Rapee & Heimberg, 1997).

1.3.1. Cognitive Behavioural Theories of Social Anxiety Disorder

Several cognitive theoretical models have been proposed to explain the development and maintenance of SAD. Certain theories posited that the reoccurring symptoms of SAD are a result of cognitive and behavioural factors, including negative self-evaluations, selective attention on the self (i.e., self-focused attention) (Clark & Wells, 1995; Moscovitch, 2009), and biased interpretation of external social cues, resulting in heightened in-situ anxious arousal (Heimberg et al., 2010; Rapee & Heimberg, 1997). As a result of these distinct cognitive and behavioural processes, individuals with SAD frequently resort to safety behaviours (e.g., excessive rehearsal prior to a talk, attempt to hide perceived blushing with makeup), or completely avoid social situations (Moscovitch, 2009) that may prevent them from obtaining corrective information (Foa & Kozak, 1986). Other models adopted a more comprehensive approach that considers the influence of early life experiences, such as parenting styles and childhood adversity patterns (Wong & Rapee, 2016) or genetic and temperamental factors (Spence & Rapee, 2016) on the formation and maintenance of SAD. There is also growing interest in exploring the role of specific emotions (e.g., shame) in the maintenance of SAD, with the possibility that some emotions may be processed differently and may contribute to the chronicity of the disorder (Rozen & Aderka, 2023). One particular theory that complements the cognitive models of SAD involves the role of attachment theory (Vertue, 2003). The fundamental human need for positive social attachment, as posited by Bowlby (2008) underscores how the formation of attachments shapes our views of self and others, subsequently influencing our interactions within the social world. The empirical cross-sectional studies have evidenced a connection between SAD symptomology and negative attachment styles. Notably, this association was found to be non-significant for other groups of patients and healthy controls (Bifulco et al., 2006; Michail & Birchwood, 2014). Considering the pathological representation of SAD, which is linked to the processing of the self and others (Heimberg et al., 2010), it is suggested that negative attachment styles acquired through early life experiences (e.g., anxious, avoidant) might influence interpretations of self and others. Consequently, these interpretations may lead to distorted threat appraisals and play a role in the development of social anxiety (Manning et al., 2017).

The early influential cognitive behavioural models by Clark and Wells (1995) suggest that individuals with SAD tend to redirect their attention from external threatening stimuli towards internal cues such as physiological reactions (e.g., increased heart rate), appearance (e.g., blushing), and thoughts (e.g., ‘they think I am shy’) when they encounter situations that trigger their fear of social interaction or performance. This mental representation of the self is often viewed from an ‘observer perspective’ as if viewing oneself from the perspective of others, as opposed to a ‘field perspective’ in which one sees things as if they were looking through their own eyes (Spurr & Stopa, 2003). Further, the mental image can be shaped by early formative experiences (or ‘failures’) stored in memory (Hackmann et al., 2000), leading to negative perceptions of one’s performance and increased situational anxiety during social encounters (Clark, 2001) (Figure 1, panel A). The theoretical model proposed by Rapee and Heimberg (1997) further incorporates the role of external cues in enhancing situational anxiety. The model recognises that social feedback during social interactions is often ambiguous, which individuals with SAD are likely to interpret adversely (Heimberg et al., 2010). These negative interpretations will likely impact how people with SAD view themselves using the observer perspective and can distort self-image over time, further exacerbating social anxiety (Schultz & Heimberg, 2008). People with SAD are also thought to compare their formed self-image to their perception of the audience’s unattainable standards for their performance. The perception of how well their behaviour matches the expectations of the audience can vary, depending on perceptions of the audience, situational demands, and their own behaviour (Heimberg, Brozovich, et al., 2014). The resulting difference in performance perceptions often leads to an overestimation of the social costs of the situation (Foa et al., 1996) (Figure 1, panel B).

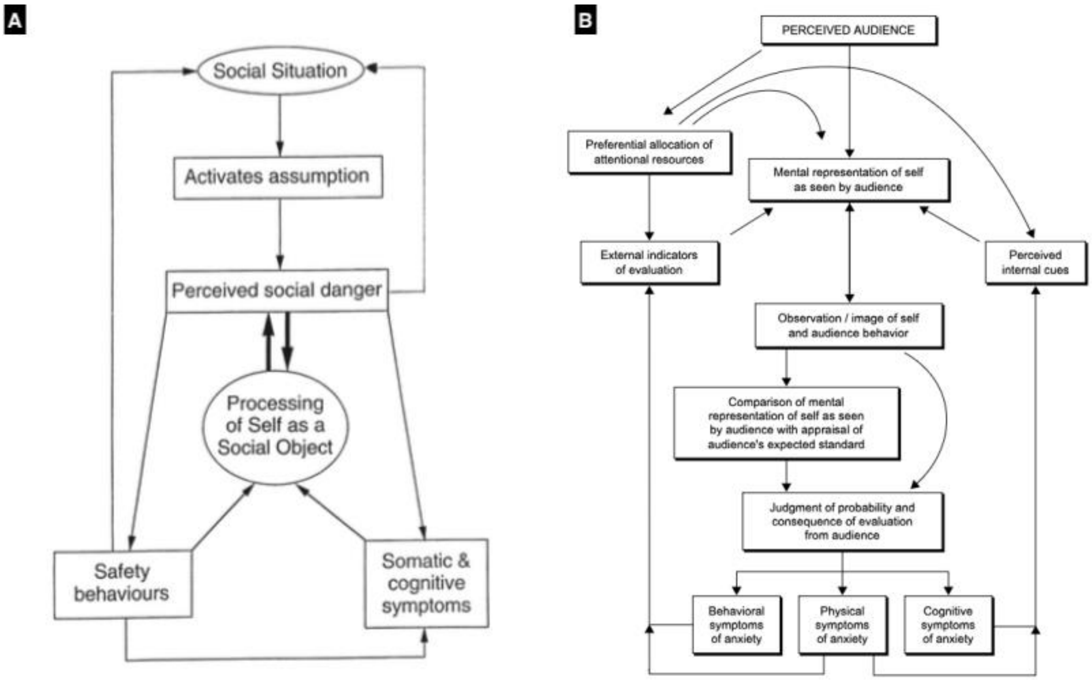
What follows next concentrates on the two types of information biases in social anxiety (i.e., attentional, and interpretational), providing a thorough examination of the empirical evidence on these biases. Since much of the research on these biases has been studied using a wide range of tasks (i.e., speech tasks, computerised tasks), the next sections will highlight the research methodologies employed. This is particularly relevant to the present thesis, which aims to develop naturalistic virtual and online socially evaluative paradigms with the aim of demonstrating their relevance to social anxiety.

1.3.2. Attentional Biases in Social Anxiety Disorder

Attention refers to selectively focusing on specific sensory input or cognitive processes, while filtering out or ignoring others (Bar-Haim et al., 2007). The cognitive theoretical frameworks of social anxiety exhibit subtle variations in their approaches to the primary source of attentional processing of negative information and threat (cf. Clark (2001) and Rapee and Heimberg (1997)). Empirical evidence indicates that SAD is associated with attentional processes that are directed towards internal (self-focused) information and/or towards external social stimuli, and there is increasing interest in understanding how these two processes may occur simultaneously and impact the disorder (Schultz & Heimberg, 2008).

Figure 1

Two Cognitive Models of Social Anxiety



Note. Panel A is reprinted from ‘A Cognitive Perspective on Social Phobia’ by Clark, D.M., 2001, *The Essential Handbook of Social Anxiety for Clinicians*, 193-218. Copyright 2001 by John Wiley & Sons Ltd, adapted from Clark and Wells (1995). Panel B is reprinted from ‘A Cognitive Behavioral Model of Social Anxiety Disorder: Update and Extension’ by Heimberg R. G., Brozovich F. A. and Rapee R. M., 2010, *Social Anxiety,* 395-422. Copyright 2010 by Elsevier. Reprint permissions from the publishers are obtained.

1.3.2.1. Perspective Taking

Self-focused attention (SFA) refers to the inclination of an individual to allocate their attention towards monitoring themselves in a detailed manner, as opposed to the features or aspects of the surrounding environment (Spurr & Stopa, 2002). The construal of the interoceptive attentional pattern involves experiencing an observer perspective, that is assumed to arise from internally generated information (e.g., rapid heartbeats), which creates a mental representation of one’s appearance and behaviour from an outsider’s viewpoint (e.g., feeling like one is shaking and being perceived as such) (Clark, 2001). Employing an observer perspective was associated with heightened levels of state and trait social anxiety (Finnbogadóttir & Berntsen, 2014). Empirical evidence suggests that a focus on or a shift to observer perspective during social encounters is particularly relevant to social anxiety (Wells et al., 1998; Wells & Papageorgiou, 1999), leading to increases in situational anxiety and more negative evaluative thoughts (Spurr & Stopa, 2003). The observer perspective exhibits resilience also in adolescent cohorts, remaining robust to age-related variations (Hignett & Cartwright-Hatton, 2008). Qualitative descriptions provide an understanding into the nature of this perspective, in which patients with social anxiety described their experiences as ‘a camera zooming in on a red, panicky face’, ‘ pictures of myself looking nervous’, or ‘looking petrified and seeing it in my eyes, shaking’, when contemplating a social encounter (Hackmann et al., 1998).

1.3.2.2. Self-focused Attention

Research has shown that both subclinical and clinical social anxiety populations report increased SFA during socially evaluative situations (Alden & Mellings, 2004; Meral & Vriends, 2022; Perowne & Mansell, 2002). Correlational studies also yielded strong positive relationships between trait social anxiety (Holzman et al., 2014; Hutchins et al., 2021) or state social anxiety during a socially evaluative task (Chen et al., 2013), and self-reported SFA (Tomita et al., 2019).

1.3.2.2.1. Causal Investigation of Self-focused Attention

SFA has been the subject of extensive investigation, utilising diverse methodologies aimed at comprehending the causal role of social anxiety (see Norton and Abbott (2016) for a review). Several methods have been used to manipulate SFA, including providing explicit or implicit instructions to divert self-focus on oneself (versus others), using self-reflecting mirrors during various socially evaluative social scenarios, or through tactual sensation probes that give (false) feedback on the change of one’s physical symptoms (e.g., heart rate) to augment internal cues (Bögels & Mansell, 2004).

Regarding the instructional manipulation of SFA, Bögels and Lamers (2002) developed two hypothetical scripts to investigate internal attention where the main character was either extremely aware of their selves in the presence of the audience (self-focused attention), or on the task and other people (task-focused attention). The study found that SFA produced higher levels of state social anxiety compared to task-focused attention. However, the study was limited in that it did not report findings analysed against a non-anxious group. In a later study conducted by Zou et al. (2007), participants with low and high blushing anxiety were instructed either to focus on themselves or on the task while engaging in a five-minute conversation with a confederate. Participants in the high blushing anxiety condition reported higher levels of anxious arousal when instructed to focus on themselves, while this effect disappeared among participants in the low blushing condition. To establish a control focus condition, certain studies instructed participants to direct their attention towards various focal points, such as the analytical aspects of scenarios (Vassilopoulos, 2008) or other individuals (Holzman et al., 2014; Woody, 1996; Woody & Rodriguez, 2000), while self-focus was indicated by directing attention towards physical symptoms. The findings of these studies were either contradictory with regards to the negative impact of self-focus on state anxiety (Vassilopoulos, 2008), or indicated that heightened self-focus during conversations resulted in increases in anxiety levels irrespective of the individual's level of social anxiety or type of control focus condition

(Woody, 1996; Woody & Rodriguez, 2000). Holzman et al. (2014) explained these inconsistent findings by suggesting that in both types of focal attention conditions, participants were still prompted to attend a prospective evaluative thought from their *own* perspective of themselves or that of others, which could introduce methodological difficulties. Moreover, the aforementioned approaches rely on direct and explicit instructions, which may not be conducive to naturalistic testing. Jakymin and Harris (2012) provided implicit instructions that did not explicitly cause anxiety over having an evaluative thought. In their experiment, participants discussed exercise with confederates, with the self-focused group discussing how exercise would impact their bodily sensations (e.g., heart rate), while the external-focused group talked about outside elements that could affect athletes' performance (e.g., climate). Their data indicated that manipulated SFA did not interact with trait social anxiety on state anxious arousal or other negative cognitions such as fear of negative evaluation. Targeting physical sensations, Wells and Papageorgiou (2001) told participants that their heart rate either increased or decreased prior to a socially evaluative encounter with a confederate. Receiving feedback about an increase in pulse rate led to greater anxiety, negative beliefs, and self-focused attention for the socially anxious group.

Bögels and Mansell (2004) recognised the ecological validity of using mirrors to enhance SFA. Despite the implicit induction of self-focus through the use of self-reflecting mirrors with this technique, its effectiveness in comprehending SFA remains uncertain. Within a socially evaluative situation using self-reflecting mirrors, some studies have reported increases in self-awareness and situational anxiety for high socially anxious groups compared to low socially anxious groups (George & Stopa, 2008), while others have reported null effects (Bögels et al., 2002).

Tactile sensation probes to enhance SFA included vibrating devices that were affixed to participants to give them misleading feedback on their physical sensations, such as heart rate levels (Makkar & Grisham, 2013), or how they appeared to others, such as the degree of blushing (Voncken et al., 2010), during socially evaluative tasks. These probes were also often used in combination with external threat stimuli to study the interactive processes (e.g., (Mansell et al., 2003); see Section 1.3.2.4.).The resulting data that utilised either physical or behavioural tactile probes failed to confirm the enhanced SFA effect, as assessed through self-report measures of attentional focus or state anxiety.

Online communication platforms have sparked interest in manipulating SFA, due to the presence of self-presenting cameras that would normally be lacking in real-life social encounters. Miller et al. (2017) conducted an experiment to compare the effects of using self-video during online interactions to the absence of any self-video. The findings indicated that enabling video feedback of the self during online social conversations increased reported self-awareness and situational anxiety, and led to greater usage of lexicon associated with anxiety. However, it should be noted that some contradictory findings were reported based on the interface used for online communication (Miller et al., 2021).

Collectively, correlational studies have indicated strong associations between SFA and social anxiety. However, study protocols attempting to manipulate SFA produced inconsistent findings, with ongoing challenges related to the effective manipulation of SFA. These challenges may stem primarily from the reliance on explicit instructions and self-report measures administered at the end of experimental protocols, which may introduce response biases.

1.3.2.3. Attention to External Threat

Theoretical frameworks have suggested that socially evaluative situations can trigger a synchronised set of psychobiological and psychosocial negative responses among healthy samples (Dickerson, 2008; Dickerson et al., 2004), as well as in anxiety-related clinical samples (Bar-Haim et al., 2007; Wong et al., 2020). Compared to healthy controls, people with SAD exhibit distinct patterns of attending to external social cues, that may be attributed to differences in how they recognise and attribute threat value (Schultz & Heimberg, 2008; Stopa et al., 2013). In addition, social anxiety symptomology highlights a fundamental apprehension of negative evaluation (American Psychiatric Association, 2013), which is believed to result in distinct attention processing patterns that prioritise seeking or avoiding evidence of evaluation (Heimberg, Brozovich, et al., 2014).

Various methodologies have been employed to investigate the attentional bias towards external social cues in social anxiety. These include computerised face tasks featuring pairs of emotional and neutral stimuli (Bantin et al., 2016), or multiple social stimuli presented simultaneously for free-viewing (Chen, van den Bos, et al., 2020), and pre-recorded audience videos of different emotional responses (e.g., neutral, negative, positive) during speech tasks within socially evaluative contexts (Chen & Clarke, 2017). In addition, recent studies have taken advantage of technology to examine selective attentional bias in immersive virtual environments (Rubin et al., 2020) and during online live social interactions (Howell et al., 2016). Within these studies, preferential attention was often quantified by analysing the response times across different stimulus categories (i.e., dot-probe paradigms) or integrating eye-tracking methods.

Considering facial dot-probe tasks, a recent meta-analysis reported significant but small effects of vigilance towards emotional stimuli over neutral stimuli among clinical and subclinical socially anxious samples (Hedge's g_{within} = 0.15), whereas no significant effects were observed for nonclinical samples and healthy controls. When tested using between-subjects designs, the group comparisons were also significant, quantifying a medium-size effect in which socially anxious people exhibited greater vigilance towards emotional stimuli, relative to control groups (Hedge's $g_{between}$= 0.49) (Bantin et al., 2016). Two particular studies (Chen et al., 2002; Mansell et al., 1999) reported no evidence of a vigilance towards emotional facial stimuli among people with SAD, but their comparison stimuli in research designs included household objects that might have resulted in the avoidance of emotional stimuli in the presence of non-emotional stimuli. Further, owing to the fact that the aforementioned studies lacked a genuine social interaction, Garner et al. (2006) tested the attentional pattern in SAD using computerised face tasks incorporating eye-tracking methodology under no social evaluative and social evaluative scenarios (i.e., anticipating a speech). The findings of their study indicated that, if social evaluation was induced, the attentional patterns were consistent with the results of previous studies, revealing heightened vigilance towards non-social objects among people with high social anxiety. However, in the absence of social evaluation stress, a contrary pattern was observed, displaying increased vigilance towards facial stimuli. In addition, free-viewing tasks with matrices of neutral and other emotional faces (e.g., anger, disgust) have been investigated using gaze patterns on areas of interest (Lazarov et al., 2016; Lazarov et al., 2021). Relative to healthy controls, the gaze duration of socially anxious patients was significantly prolonged on threat-related faces, whereas looking at neutral faces resulted in similar viewing time. The aforementioned studies with predetermined viewing time might lead to bias in the data, therefore some researchers utilised free *time* viewing tasks, in which participants would look at the faces of different emotions, one at a time. Attention bias was deemed present if the view-time of a given stimulus was longer (Grisham et al., 2015). In general, people with high social anxiety avoided emotional stimuli (i.e., shorter viewing time) relative to people with low social anxiety, especially for negatively valanced faces. Likewise, Elias et al. (2021) tested the visual attention patterns of people with social anxiety, using a Facebook profile containing social and non-social static visual stimuli. The findings from the gaze data revealed that, compared with non-anxious participants, socially anxious participants demonstrated a viewing pattern favouring social pictures less, reflecting an attentional avoidance tendency.

Pe-recorded videos have also been utilised in many instances as a more dynamic type of stimuli that also can accommodate a socially evaluative interaction (Chen et al., 2016; Chen, Thomas, et al., 2015; Weeks et al., 2019). For instance, Chen, Thomas, et al. (2015) introduced a novel paradigm in which participants gave a talk to a pre-recorded dynamic audience displaying positive, neutral or negative emotional gestures. Gaze data revealed that people with SAD exhibited a pattern of avoidance, spending more time looking at non-social regions during their social interaction (Chen, Thomas, et al., 2015). Further, Chen et al. (2016) reported that during the onset of emotional gestures, non-anxious participants displayed a greater inclination to orient their gaze towards positive stimuli relative to negative stimuli, whereas this initial orienting pattern was absent among the clinical socially anxious group. Using immersive virtual reality within a public speaking environment, Rubin et al. (2020) found that the interaction between fear of public speaking and gaze on audience members was significant only in the first three minutes of the speech task. This finding aligns with the available empirical evidence that although people with social anxiety are vigilant to threat-related external stimuli in the first instance (e.g., facial expressions), they then resort to some avoidance strategies to reduce their in-situ anxiety (i.e., vigilance-avoidance hypothesis) (Chen & Clarke, 2017). Using online communication, Howell et al. (2016) investigated the gaze patterns of people with trait social anxiety during a live, dyadic interaction. The results of the study indicated that participants with social anxiety exhibited reduced attentional maintenance to confederate eye regions, thereby suggesting a tendency to avoid eye contact during social interaction.

It is important to note that, although many studies utilised established computer-generated facial sets such as the Karolinska Directed Emotional Faces database (https://kdef.se/) (Lundqvist et al., 1998), gaze-mediated orienting of attention is reported to alter as a function of various factors, including the characteristics of the cueing faces (Dalmaso et al., 2020). For instance, Demos et al. (2008) found that participants' amygdala activity in response to facial stimuli with larger pupil size showed an increased activity compared to stimuli with original pupil size, even after participants reported that they were not aware of this manipulation. In social anxiety context, recent work reported that participants' perception of the gaze of stimuli during a social interaction (measured by self-reports involving whether participants perceived the gaze using a two-point scale yes/no among other variables such as whether participants focused on bodily sensations) was the most significant predictor of biased attentional processing for people with high social anxiety (Nanamori et al., 2023). Therefore, inconsistencies in the literature may be attributed to a lack of carefully controlled facial stimuli. In addition, scholars have reported that the gaze direction of the face stimuli (e.g., direct versus averted gaze) resulted in different gaze orienting patterns among anxious and socially anxious populations (Fox et al., 2007; Holmes et al., 2006; Roelofs et al., 2010). This stresses the importance of creating naturalistic, ecologically valid face stimuli that are close to real-life social interactions when studying SAD.

In light of the existing literature, it is clear that the attentional processing among individuals with social anxiety is distinct. Numerous investigations have utilised various tasks to examine this phenomenon. Given that available evidence gives support for both vigilant and/or avoidant patterns of external attention, it can be inferred that the contrasting findings might be due to the methodological differences (e.g., facial set differences, dynamic/static face stimuli), variations in comparison stimuli (e.g., emotional faces versus household objects/neutral faces), and the need to account for the time-course changes in attentional bias during social evaluative situations.

1.3.2.4. Attentional Balance Between Internal and External Threat Processing

The presence of supportive evidence for both external and internal attentional differences in social anxiety underscores the importance of investigating the interaction between these processes during social situations to clarify the discrepancies between Clark et al. (1995) and Heimberg et al. (2010). Investigating the interplay between internal and external attentional processes, researchers developed novel probe detection paradigms. To draw the attention to self (i.e., internal cue, SFA), subjects were often shown visual stimuli of their physical symptoms (e.g., hand sweating) or were connected to a vibrating device. Subjects were then informed that changes in their physical symptoms (e.g., heart rate or skin conductance) would ostensibly be reflected in the visual stimuli or via the vibrating device to which the subjects were connected. External probes mainly involved detecting a superimposed letter presented within visual stimuli on a computer screen (e.g., household objects versus angry, fearful, or happy human faces) (Mansell et al., 2003; Pineles & Mineka, 2005; Vriends et al., 2016). However, these paradigms were limited in incorporating socially evaluative situations (e.g., a public speaking task). To address this limitation, researchers implemented high or low socially evaluative conditions by informing participants that they would give a speech after the computerised task (i.e., high social evaluation), or that they would wait for the experimenter to get ready (i.e., low social evaluation). The probe-detection tasks typically began after participants had been given instructions either to prepare a talk or wait for the experimenter. The findings revealed that individuals with high levels of social anxiety demonstrated faster reaction times to tactile probes, indicating internal cues compared in contrast to external visual probes, as compared to individuals with low levels of social anxiety. Notably, some research reported that this effect occurred solely during high socially evaluative situations (Mansell et al., 2003; Mills et al., 2014), while others reported this effect to occur regardless of the level of socially evaluative conditions (Pineles & Mineka, 2005). However, these paradigms were deemed to have reduced ecological validity owing to the absence of genuine socially evaluative interactions (Schultz & Heimberg, 2008).

To address the issue of ecological validity, Deiters et al. (2013) employed a novel approach simultaneously manipulating internal and external cues *during an actual speech task*. In this paradigm, participants were presented with an external probe in the form of a flashing light affixed to the head of an audience member listening to the speech, rather than on a computer, as is typically done in probe tasks. This setup required the subjects to avert their gaze towards the audience member's face to detect the probe. Internal attention was manipulated via a bone-conducting device that provided tactile feedback. Participants were informed that any changes in the device's vibrations corresponded to physical changes that they experienced during the public speaking task. The findings showed that people with high social anxiety demonstrated greater propensity for the detection of internal cues during speech anticipation compared to those with low social anxiety, while reaction times to external probes were similar across both groups. Interestingly, the biased processing of internal cues disappeared among those with high social anxiety during the speech. A recent work by Lin et al. (2021) argued that previous studies on simultaneous internal and external attentional processing had focused on different types of neural processing (e.g., tactile versus visual probes), resulting in a lack of direct comparability. They developed a feedback wave system to investigate the trade-off between internal and external attentional processing during a live video chat, relying on eye tracking. The experimental protocol involved presenting a pre-recorded audience to participants as if they were present in real-time, and subsequently displaying their feedback in the form of negative, positive, or neutral waveforms in separate cells whilst the participants give a talk. Participants' internal attentional processes were manipulated using electrodes attached to them, with the resulting data being also displayed in waveforms within dedicated cells of the interface. Participants were trained on the meaning of the wavelengths. Fixation times during the participants' speech and re-watching conditions (i.e., low social evaluation) were quantified by defining areas of interest for each cell. The findings indicated that internal cues were fixated on for longer than any other external feedback waves, particularly during the speech phase. These findings might confirm the predominant role of SFA, especially in socially evaluative situations, for people with social anxiety. The feedback wave system developed by Lin et al. (2021) is a valuable and effective tool for studying attentional processing in a controlled and standardised way, despite not providing a fully realistic representation of social evaluation in real-life situations.

Online communication platforms offer a promising avenue for investigating the interactive processes of internal and external attention in a naturalistic testing environment. The distinct feature of a self-video feed that these platforms offer holds the potential to enhance SFA. Furthermore, these platforms afford the opportunity to manipulate the external threat cues of an audience while preserving ecological validity. Recent studies have shown interest in exploring the potential of online communication platforms for investigating attentional processes. Vriends et al. (2017) explored whether SFA can be enhanced for subclinical and clinical social anxiety populations within online communication platforms. SFA was directly measured through eye-tracking to determine if participants were focusing on their self-image, the video of their conversation partner, or other areas of the computer screen. Sub-clinical social anxiety samples dwelled on their own video more frequently during the critical phase of the conversation. This dwelling has expanded to four phases of the conversation task (i.e., warm-up, positive, critical, active) for people with a SAD diagnosis when compared to control groups (i.e., low socially anxious sample). This suggests that how one prioritises self-referential information, such as one's appearance to others, may vary based on the valence of the external social cues. Contrarily, Azriel et al. (2020) found a different trend, as their data showed that people with SAD spent less time dwelling and fixating on their own image compared to the confederate's video or other areas of the computer screen, and that this trend was not observed among people with low social anxiety. It is worth noting that the study design of Azriel et al. (2020) did not involve any audience feedback (e.g., critical, positive). Instead, participants were exposed to an audience with a standard neutral appearance, which could explain the incongruent findings to Vriends et al. (2017).

To summarise, the investigation of the trade-off between external and internal attention in the involvement of SAD has been explored through paradigms with limited ecological validity. Despite this limitation, the available empirical evidence appears to support Clark's theoretical model (Clark et al., 1995; Clark, 2001), which suggests that selective attentional bias towards self-referential information might be a more prominent factor as opposed to the processing of external social threats in social anxiety symptomology. Further, online communication platforms might provide naturalistic testing overcoming ecological validity, and have emerged as a promising avenue for investigating interactive attentional processes in SAD.

1.3.3. Interpretational Bias in Social Anxiety Disorder

Interpretation bias refers to the inclination to view ambiguous or neutral stimuli as threatening or dangerous. The existence of interpretation biases has been demonstrated across different age groups of people with SAD including children and adolescents (Stuijfzand et al., 2018), and adults (Chen et al., 2019), and a recent meta-analysis found a large effect size in the relationship between interpretation bias and subclinical and clinical socially anxious adult samples (Chen, Short, et al., 2020). This bias has been shown to be specific to SAD as opposed to other anxiety-related disorders (Stopa & Clark, 2000), including obsessive compulsive disorder (Amin et al., 1998) and as opposed to mood-related disorders such as depression (Kanai et al., 2010; Voncken et al., 2007). Interpretation bias in the social anxiety literature has mainly been investigated by presenting participants with ambiguous words, incomplete social scenarios, and computerised tasks involving facial expressions, photographs, or pre-recorded videos (Amir & Bomyea, 2010; Hirsch et al., 2016; Kuckertz & Amir, 2014). The responses are quantified on subjective data such as ratings/rankings of the valence of the social scenarios or objective data (i.e., reaction times) to identify the emotional valence or classification of the stimuli.

Considering written vignettes, Amin et al. (1998) presented participants with social scenarios that were ambiguous in terms of their social implications (e.g., 'someone you are dating says hello to you…') or non-social implications (e.g., 'you get your cable bill and notice that…'). Participants would rank-order the three pre-determined possible interpretations of these scenarios. One interpretation was always negative (e.g., 'they feel sorry for you'), whilst the other two were either neutral (e.g., 'they say hello to everyone') or positive (e.g., 'they want to get to know you.'). The findings favoured a greater likelihood of the negative interpretation of the ambiguous scenarios with social implications for people with social anxiety relative to the control groups. If the scenario had a non-social implication, no difference between the groups was observed. Consistent content-specific findings have been reported in other studies that used written scenarios (Voncken et al., 2007; Voncken et al., 2003) or within newly developed similar paradigms (Dapprich et al., 2022). Stopa and Clark (2000) extended upon these findings by demonstrating that people diagnosed with SAD tend to interpret mildly negative social scenarios in a catastrophic way, in contrast to those with other anxiety-related disorders or those who were healthy controls. In addition, Badra et al. (2017) reported that people high in social anxiety were more likely to complete ambiguous written scenarios with a negative ending rather than with a positive ending, compared to the controls.

Further, scholars have suggested that this bias of people with social anxiety might be due to a lack of benign recognition of ambiguous/neutral events (Huppert et al., 2003). Beard and Amir (2009) developed the Word Sentence Association Paradigm (WSAP) to investigate this. In the task, participants would decide if a prime word that suggested a threat or a benign meaning (e.g., weird/cool) was related to a subsequently presented sentence that was ambiguous in nature (e.g., 'someone looks at you as you walk by'). An interpretation bias was deemed to exist if the participants were more likely to endorse interpretations that suggested a threat rather than those that were benign, and if they responded more quickly when choosing the threat interpretations and rejecting the benign interpretations (measured by reaction times). The likelihood of endorsing a threat meaning was consistently higher in subclinical and clinical social anxiety populations relative to control groups in studies that used modified WSAP paradigms (Amir et al., 2012; Chen et al., 2019; Huppert et al., 2007), although response latencies in deciding the relatedness of threat and benign interpretations to the ambiguous sentences were comparable for the SAD samples and control groups (Amir et al., 2012; Chen et al., 2019; Chen, Short, et al., 2020). In addition to presenting ambiguous scenarios, researchers aimed to investigate the assumption that SAD would be associated with an inclination to interpret *positive* social events in a more negative fashion (Alden et al., 2008; Vassilopoulos & Banerjee, 2010). For instance, Voncken et al. (2003) presented written scenarios to participants that were positive, negative or neutral in nature. The findings showed that people with SAD demonstrated a content-specific interpretation bias, in which all social scenarios were interpreted negatively, regardless of their emotional valence, relative to controls.

Other research utilised visual stimuli to examine interpretation bias, which was presumed to have more ecological validity in social interactions (Chen, Short, et al., 2020), including pre-recorded video vignettes and computerised tasks featuring facial expressions. Amir, Beard and Bower (2005) conducted a study using pre-recorded video scenarios with negative, neutral, and positive content, in which a confederate provided commentary on the participants' actions. The results were in line with the studies that used written scenarios, in that people with SAD rated the negative and ambiguous video content more negatively compared to the controls, while no significant differences were observed between the two groups for positive videos. Studies that used computerised paradigms to investigate the emotional response bias towards ambiguous or negatively valanced faces (e.g., angry) were not as consistent. Some studies found that those with high levels of social anxiety perceive ambiguous and negatively valanced faces as more negative (Heuer et al., 2010; Maoz et al., 2016), while others did not find such an association (Jusyte & Schönenberg, 2014). In addition, people with SAD were less accurate in classifying negatively valanced expressions (e.g., fearful, angry) relative to the controls (Bell et al., 2011; Bourke et al., 2012; Garner, Baldwin, et al., 2009; Peschard & Philippot, 2017), except in the research by Qiu et al. (2018). While computerised face tasks have received criticism for lacking a social context (e.g., (Chen et al., 2019)), some have attempted to create a more realistic social evaluative context by informing participants that they would be giving a speech after completing the task (Vassilopoulos, 2011). Kanai et al. (2010) studied interpretation bias within a more naturalistic real-life public speaking paradigm that included a real socially evaluative element, with a confederate presenting ambiguous social behaviours (e.g., scratching head). After the talk, participants were asked to provide their interpretations of the confederate’s behaviour using a combination of open-ended questions and rating scales. A high level of social anxiety was associated with more negative and threating perceptions of the behaviour relative to low levels of social anxiety.

Taken together, it is widely agreed upon that interpretation bias exists for SAD. However, the types of stimuli and measures used have been diverse, with limited ecological validity. As a result, there is a need for more naturalistic testing methods that can capture cognitive and behavioural functioning as social events unfold. This thesis recognises the need for more naturalistic testing methods in studying SAD, and proposes promising areas for developments in using technology to create more realistic testing environments.

1.3.4. Performance Evaluations

The available empirical evidence is focused on two primary questions in studying the link between social anxiety and performance evaluations: (a) whether people with SAD exhibit actual performance deficits during social evaluative scenarios; and (b) whether people with SAD underestimate their social performance. To address these questions, researchers have often utilised speech tasks to investigate anxiety induced performance deficits from the ratings/perspective of people with clinical and subclinical social anxiety, and of external observers using subjective self-report data.

Some evidence supported the first assertion that people with SAD actually perform poorly, as reported by external observers who perceived their performance as comparatively inferior to that of non-clinical control groups (Cheng et al., 2017; Norton & Hope, 2001; Stopa & Clark, 1993; Voncken et al., 2008), while early studies reported comparable proficiency in performance between people with SAD and healthy controls (Rapee & Lim, 1992; Strahan & Conger, 1998).

The second investigation pertaining to the potential underestimation of performance among SAD samples was examined through a comparison of high socially anxious individuals' self-perceptions of their performance, in relation to low socially anxious individuals or control groups. A recent correlational study by Howell et al. (2016) indicated that trait social anxiety was inversely related to participants' self-evaluations of performance. Again, the evidence showed that after engaging in a conversational social interaction or an impromptu speech, people with high social anxiety appraised their performance more poorly relative to a non-anxious control group (Brozovich & Heimberg, 2011; Cheng et al., 2017; Perini et al., 2006; Spurr & Stopa, 2003). In addition, prior work also explored the discrepancy between participants' performance ratings and those of external observers, with regards to high and low socially anxious individuals, as well as healthy control groups (i.e., performance underestimation). The findings were consistent demonstrating that socially anxious individuals' performance ratings are lower than independent ratings (Alden & Wallace, 1995; Clark & Arkowitz, 1975; Gavric et al., 2017; Rapee & Lim, 1992; Stopa & Clark, 1993; Voncken & Bögels, 2008), and that the perception of this negative performance progressively became more severe for SAD samples in time (Cody & Teachman, 2011). In addition, Voncken and Bögels (2008) found that, depending on the context of the task at hand, the perceptions of one's performance deficits might vary. That is, their data showed that more interpersonal conversations actually elicited performance deficits among high socially anxious people, whilst performance-related social interactions did not lead to performance deficits but resulted in more negative cognitive distortions (e.g., anxious appearance). Further, the task context might also influence performance appraisals, particularly among high socially anxious groups. Thompson and Rapee (2002) reported that structured social interactions, such as role-play scenarios, were associated with less impaired performance compared to unstructured, impromptu social interactions.

It is worth noting that evaluation of performance as a feared *consequence* in SAD (Moscovitch, 2009) has typically been investigated by incorporating other preceding dysfunctional processes of the disorder. According to the cognitive theories of social anxiety, primary cognitive processes that involve the processing of self-related and/or external stimuli evoke heightened anxious arousal, which ultimately leads to performance deficits among people with SAD (Clark & Wells, 1995; Heimberg et al., 2010; Rapee & Heimberg, 1997). Heimberg et al. (2010) further argued that people with SAD tend to avoid or escape social interactive situations, which results in performance deficits (see Wong and Rapee (2016), Table 6 for a comparison, p. 90). In this regard, empirical investigations of performance appraisals within the context of other biases have often been studied, although findings remain inconsistent. For instance, Daly et al. (1989) showed that increased SFA results in poor performance among people with high public speaking anxiety, however, experimentally manipulated SFA or observer perspective among high socially anxious samples did not influence negative performance appraisals (Holzman & Valentiner, 2016; Spurr & Stopa, 2003; Woody, 1996). Voncken et al. (2010) further suggested that self-related negative cognitions, but not SFA, predicted the link between trait social anxiety and performance appraisals. In terms of anticipatory processing of the social event, for instance, Brown and Stopa (2007) reported that an anticipation phase (versus no anticipation phase) before a speech task may aid with superior performance appraisals among high social anxiety samples. Further, performance evaluations were also explored in the context of post-event processing, where performance appraisals were suggested to result in negative rumination of the social event after a while among high socially anxious people (Perini et al., 2006). To summarise, performance evaluations might be impacted by other additional cognitive factors that people with SAD possess.

1.3.5. Negative Ruminations

1.3.5.1. Anticipatory Processing

Cognitive theories suggest that when people with SAD anticipate a forthcoming social evaluation scenario, the anticipatory processing (AP) mechanism, which is a mental review process, is activated (Clark & Wells, 1995; Heimberg et al., 2010; Rapee & Heimberg, 1997). This mental review includes reviewing potential outcomes of the forthcoming social interaction, focusing on the level of anxiety, recalling past social failures, having negative self-images, and predicting unfavourable performance and negative social consequences (Clark & Wells, 1995). The content of AP has empirically been supported, in which socially anxious people experienced recurrent and intrusive thoughts about the upcoming event, which interfered with their ability to concentrate and heightened their anxiety levels (Vassilopoulos, 2004). The most recent review articles have highlighted a positive association between trait social anxiety and AP (Penney & Abbott, 2014; Wong, 2016). In addition, the severity of AP negatively predicted treatment outcome among clinical social anxiety samples, implying the role of AP in SAD symptomology (Wong et al., 2017).

In maintaining SAD, experimentally induced AP (i.e., instructing participants to think about what could go wrong in the impending social interaction) resulted in heightened situational anxiety during a speech task among high socially anxious people relative to a distraction task (i.e., reading and putting paragraphs in the correct order to create a meaningful chapter). No different patterns of anticipation and distraction tasks were observed among low socially anxious people (Vassilopoulos, 2005). Likewise, Brown and Stopa (2007) instructed both low and high socially anxious participants to give two speeches, one with a 10-minute anticipation period and one without. High socially anxious individuals experienced heightened anxiety when anticipating the social situation (versus no anticipation), while the low socially anxious group did not exhibit any significant patterns of difference. These findings suggest a causal role of AP in SAD symptomology.

Despite the preliminary evidence supporting the relevance of AP in social anxiety, which is consistent with cognitive theoretical frameworks, AP has received limited attention, possibly due to methodological challenges (Wong, 2016). One such challenge is investigating the relationship between other cognitive biases, such as attentional biases of internal cues and external threat, and AP, as implied by cognitive theories (Clark & Wells, 1995). Mills et al. (2014) addressed this relationship by utilising a computerised probe detection task. They presented participants with neutral versus emotional faces to account for external bias, and false heart rate feedback waves were quantified for internal focus. Participants completed the computerised task twice, with an induced state of AP in between. AP manipulation involved thinking about specific prompts for their 'upcoming' talk, whereas a control distraction task asked participants to think about various non-social scenarios such as the shape of a large black umbrella. The results showed that AP induction resulted in a bias for internal information (i.e., heart rate feedback) for people with high social anxiety (versus low social anxiety), whereas no attentional differences were observed during the distraction task for biased processing. This finding implies that AP might be responsible for the activation of internal focus for SAD. However, as mentioned before (Section 1.3.2.4), the paradigms used in the study, such as the computerised probe detection task, may not fully capture all phases of attentional processing (Penney & Abbott, 2014). Moreover, investigations into the impact of AP on social anxiety are somehow limited in their interpretation, as studies have primarily relied on self-report questionnaires with no social evaluative scenario (Vassilopoulos et al., 2017).

1.3.5.2. Post-event Processing

As AP is a pre-event rumination that occurs before a social evaluative interaction, people with SAD also engage in post-event processing (PEP) following a social evaluative event. While PEP is reported in other clinical conditions such as depression (Smets et al., 2012), it is suggested to have diagnostic specificity among socially anxious groups based on the content of ruminations (Kocovski & Rector, 2008). In SAD, PEP as a post-mortem mental review process involves reviewing the outcomes of the occurred social interaction, focusing on the level of anxiety experienced, negative self-cognitions, and recollections of past social failures (Clark & Wells, 1995), which results in the social interaction being recalled more negative than it actually was (Hofmann, 2007). These cycles of events often lead to avoidance of similar future social interactions (Rachman et al., 2000).

PEP has been more extensively studied than AP (Wong, 2016), and empirical support has been found for its role in the involvement of SAD maintenance (Brozovich & Heimberg, 2008; Penney & Abbott, 2014). PEP is mainly investigated through self-report measures, daily diaries, socially evaluative scenarios tested in laboratories, and experimental manipulations of PEP (Brozovich & Heimberg, 2008).

Correlational self-report studies gave evidence of the relationship between PEP and situational anxiety among clinical social anxiety samples (Chen et al., 2013), as well as subclinical samples (Brozovich & Heimberg, 2011). Studies on PEP within lab-based social evaluation tasks demonstrated that people with clinical and subclinical social anxiety exhibit increased levels of PEP following social interactive encounters when compared to low socially anxious groups and non-anxious controls (Dannahy & Stopa, 2007; Edwards et al., 2003; Gavric et al., 2017), with the negative impact of PEP persisting for up to a week in clinical SAD groups (Gavric et al., 2017). Utilising electronic diaries, Helbig-Lang et al. (2016) investigated the PEP content among patients diagnosed with SAD, where they would record each time that the participants encountered a stressful social situation over the course of a week. Performance situations relative to conversational scenarios significantly increased the PEP records of participants, although other features of a given stressful social situation (e.g., planned, unplanned, number of audience) did not predict heightened PEP. This finding is consistent with Makkar and Grisham (2011), in which the recorded PEP after a speech scenario relative to a conversation scenario was more severe.

One study by Brozovich and Heimberg (2011) examined the phenomenon of PEP through experimental induction, in which participants were asked to reflect on their experience of a speech task while focusing either on themselves or on the task. Although this design inherently involves SFA, the findings revealed that when high socially anxious participants recalled the socially evaluative task while focusing on themselves (versus on the task), they reported fewer positive feelings about the social event, whereas no pattern was observed among low socially anxious participants. It might also be pertinent to note here that, although direct links between trait social anxiety and PEP have been established (Chen et al., 2013), PEP was implied to have unique predictors within its link to trait social anxiety. Previous studies have primarily focused on the mediating effects of performance appraisals and fear of negative evaluation in the link between trait social anxiety and PEP, as noted by (Penney & Abbott, 2014).

Taken together, these two cognitive processes, AP and PEP, appear to be involved in social anxiety maintenance. Both pre and post negative ruminations showed some evidence in their intricate relation to other biased cognitive processes of SAD. There is less research on AP, and PEP evidence varies depending on the nature of the socially evaluative task at hand (e.g., performance related, conversational).

1.3.6. Summary: Theories and Biases in Social Anxiety Disorder

To summarise, it is evident that social anxiety symptomology and maintenance are influenced by a combination of biases, primarily consistent with the cognitive theoretical frameworks of SAD. In the current section, I have emphasised the methodological variations in examining these biases, as one potential reason for nondefinitive conclusions. Importantly, the major challenge for assessing cognitive biases was the need to integrate a naturalistic socially evaluative situation, and to measure these biases as social events unfold. While the current thesis does not directly address how these processes occur together, the provision of evidence-based anxiogenic testing paradigms for SAD may facilitate the systematic exploration of these processes. The next section will detail laboratory paradigms that can produce anxiety and might be used to test cognitive biases in more naturalistic social settings.

1.4. Experimental Human Models of Anxiety

Anxiety is a core maintenance mechanism of most psychiatric illnesses (Stein & Craske, 2017), including social anxiety (Stein & Stein, 2008). Experimental testing of theoretical frameworks underlying the mechanisms of pathological anxiety is essential for scientific, evidence-based research that could ultimately help identify more precise treatment strategies. While animal models are useful for enhancing our understanding of anxiety (Campos et al., 2013; Garner, Möhler, et al., 2009), translational research has suffered from poor predictive validity when using animal models. The challenges with animal testing were particularly observed in the field of drug development, which has led to unsatisfactory outcomes and side effects (Baldwin & Abou-Aisha, 2019). In addition, theoretical frameworks of anxiety often rely on higher order cognitive processes such as worry, which cannot be practically modelled in animals, limiting construct validity (Grillon et al., 2019; Nestler & Hyman, 2010). Recently there has been a growing interest in 'experimental psychopathology' which uses healthy humans in bridging translational research (Grillon et al., 2019). In particular, human models of anxiety have been suggested to offer better model validity, make more efficient use of resources (Akhtar, 2015), and avoid the ethical concerns associated with invasive techniques that may cause animal suffering (Akhtar, 2011). Moreover, these models provide a benefit in terms of convenient recruitment for research, as clinical research can be expensive, time-consuming, and complicated by the presence of comorbid symptoms and ongoing medical treatments. The importance of human anxiogenic models in scientific research is widely recognised, and joint efforts have been made to create a database of such protocols in Europe (Bonapersona et al., 2022).

In the next chapter I will study the available literature on two anxiety inducing protocols categorised by the type of anxiogenic stimuli. Several types of human anxiogenic models have been suggested thus far, including psychological challenges, pharmacological challenges, and physiological challenges, each targeting different defence mechanisms (i.e., body acidosis, social threat, acute pain) (Siepmann & Joraschky, 2007).

1.4.1. Pharmacological Models

Pharmacological challenges refer to the administration of substances that are known to increase anxiety levels. For example, oral ingestion of caffeine was reported to produce robust increases in negative cognitions (e.g., nervousness) and in anxiety levels (Charney et al., 1984), with a degree of specificity to the symptomology of panic patients (Klevebrant & Frick, 2022). Likewise, yohimbine, an ingredient extracted from the bark of a South American tree and known for its alpha-adrenoceptor activity, has been used as an experimental human model for inducing anxiety that has been linked to restlessness (Charney et al., 1983), in which the effects closely compare with the symptoms of panic patients (Bandelow et al., 2017). More recently, it has been documented that specific doses of carbon dioxide (CO_2) gas enriched with normal air can safely induce anxiogenic reactivity and negative subjective responses comparable to those experienced in anxiety-related disorders (Baldwin et al., 2017). The following section examines current CO_2 research as an anxiogenic paradigm, which has yielded promising findings in the realm of anxiety-related illnesses.

1.4.1.1. CO_2 Challenge

A frequently employed experimental approach used to study anxiety involves exposing individuals to normal air with elevated concentrations of CO_2 gas. The inhalation of varying levels of CO_2 allows for exploration across the broad spectrum of anxiety disorders, with higher CO_2 doses (e.g., 35%) triggering panicogenic symptoms akin to panic disorder (Cosci et al., 2019; Valdivia-Salas et al., 2014; Van den Hout & Griez, 1984), while lower doses (5% to 8%) produce a more broad anxiogenic symptomology (Bailey et al., 2005; Poma et al., 2005). Particularly, the inhalation of regular room air enriched with 7.5% CO_2 for 20 minutes was found to increase heart rate, blood pressure, and subjective anxious states such as worry and fear, while reducing positive mood among healthy people (Bailey et al., 2006; Bailey et al., 2005). Different concentrations of CO_2 gas have been utilised as an acute anxiogenic or panicogenic paradigm in various research contexts, including detangling the bipolar and panic comorbidity (MacKinnon et al., 2007), testing the role of acute stress in balance and postural control (Taylor et al., 2023), and exploring the pharmacological anxiolytic effects of alcohol intake (Cosci et al., 2004). In addition, using this paradigm, researchers gained a greater understanding of the different components of therapeutic interventions (e.g., open monitoring, acting with awareness) (Ainsworth et al., 2015; Chow et al., 2018), and therapeutic placebo effects on acute anxiety (Huneke et al., 2018).

Due to its similarity to generalised anxiety disorder (GAD) symptomology in inducing subjective worry and restlessness (Bailey, Kendrick, et al., 2007), the 7.5% CO_2 challenge has mostly been used in research investigating GAD in particular within drug studies (Papadopoulos et al., 2010). When tested on people diagnosed with GAD, the 20-minute protocol robustly increased subjective anxiety and panic symptomology across two testing days, and yielded trends towards meaningful differences on cortisol levels (Seddon et al., 2011). Relatedly, 7.5% CO_2 inhalation was reported to be responsive to certain anxiolytic drugs for GAD when tested on healthy volunteers (Bailey, Kendrick, et al., 2007; Diaper, Osman-Hicks, et al., 2013; Diaper, Papadopoulos, et al., 2012), which could aid in the translation of preclinical findings to clinical applications. People with SAD have also been found to exhibit sensitivity to CO_2 gas (Nutt et al., 1998). Although there has not been much research on the effects of the gas in individuals with SAD, 35% CO_2 administration resulted in a stronger fear response in people with SAD compared to healthy controls (Schmidt & Richey, 2008). However, the effects were not as significant as in panic patients (Schutters et al., 2012).

Even though there have been suggestions that the 7.5% CO_2 challenge closely mirrors GAD (Bailey et al., 2011), and has been frequently tested in that context, this paradigm also facilitated investigations of the effects of acute anxiety on various subjective and cognitive measures, including information processing (Attwood et al., 2015; Attwood et al., 2013; Easey et al., 2018; Savulich et al., 2019), interpretational bias (Attwood et al., 2017; Cooper et al., 2013), attentional functioning (Cooper et al., 2011; Diaper, Nutt, et al., 2012; Garner et al., 2011; Garner et al., 2012), language processing (Mattys et al., 2013), and decision making (Bruehl et al., 2015; Brühl et al., 2015). As distinct patterns of the aforementioned processes are observed across a wide range of anxiety disorders (Bar-Haim et al., 2007), the CO_2 challenge has provided valuable insights in this regard. Table 2 summarises the key findings. More related to the current thesis, for example, Cooper et al. (2013) conducted a study in which participants rated the level of negative or positive activity in inherently ambiguous closed-circuit television (CCTV) videoclips whilst inhaling either 7.5% CO_2 or normal room air. The findings showed that increased ratings of negative/suspicious behaviour were evident for participants instructed to rate negative activity under the gas condition relative to air, whereas no differences were observed when participants were instructed to rate positive activity. Using a computerised face task, Attwood et al. (2017) reported that, under gas conditions, participants perceived faces as negative (i.e., anger) rather than positive (i.e., happy) in a two-choice forced task involving an ambiguous angry-happy blend of faces. However, within a social evaluation learning task, Button et al. (2016) failed to find a more negative bias towards self-related information as a function of gas administration.

Table 2

Summary of Findings of Studies Utilised the 7.5% CO_2 on Healthy Volunteers

Authors	Subjective		Cognitive		Objective		Notes
	Anxiety	Mood	Task	Behaviour	BP	HR	
Garner et al. (2011)	↑	↑ negative affect ↓ positive affect	Emotional antisaccade task	Increased orienting toward negative stimuli (versus neutral stimuli) and slower orienting away from negative stimuli	Systolic ↑ Diastolic X	↑	7.5% CO_2 challenge might lead to selective attention to threat
Cooper et al. (2011)	↑	↑ negative affect, fearful, anxious, feeling like leaving, tense, nervous, worried, stressed. ↓ positive affect	Dot-probe task (facial stimuli)	An attentional bias to emotional facial expressions relative to neutral faces regardless of valence (happy, angry, and fearful)	Systolic ↑ Diastolic ↑	↑	7.5% CO_2 challenge might result in negative attentional bias although replication efforts failed to find the vigilant effects in Experiment 2.
Garner et al. (2012)	↑	↑ negative affect ↓ positive affect	Attention network task	Alerting and orienting network function, but not executive control	Systolic ↑ Diastolic X	↑	7.5% CO_2 challenge might selectively enhance the functioning of discrete human attention
Diaper, Nutt, et al. (2012)	↑	↑ fearful, feeling like leaving the room, anxious, paralysed, panic symptoms ↓ happy, relaxed	Tracking and target identification task	Comparable performance in tracking task, more correct responses in target identification task but lower reaction time	Systolic ↑ Diastolic ↑	↑	7.5% CO_2 challenge might result in focused attention
			Radar task	Comparable reaction times to target activity			

Authors	Subjective		Cognitive		Objective		Notes
	Anxiety	Mood	Task	Behaviour	BP	HR	
Attwood et al. (2013)	↑	-	Glasgow Face Matching Test	Decreased performance for hits and not false alarms in identifying faces	Systolic ↑	↑	7.5% CO_2 challenge might result in poor initial processing and encoding of faces
Diaper, Nutt, et al. (2013)	↑	↑ anxious, irritable, panic symptoms ↓ alert	Combat computer game (group setting)	Fewer bullets were fired during the game	-	↑	7.5% CO_2 challenge might lead to 'frozen' activity in group settings (self-preservation)
Cooper et al. (2013)	↑	↑ fearful, anxious, feel like leaving, tense, nervous, worried, stressed ↓ happy	Neutral video clips of CCTV for suspicious activity ratings	More ratings for negative suspicious activity, no rating differences for positive suspicious activity	Systolic X Diastolic X	↑	7.5% CO_2 challenge might lead to negative interpretation bias
Mattys et al. (2013)	↑	-	Speech perception task	Poorer phoneme discrimination and greater reliance on lexical knowledge	Systolic ↑	↑	7.5% CO_2 challenge might worsen attentional control and distract listeners away from the phonetic detail of the signal
Pinkney et al. (2014)	↑	↓ positive affect	Affective startle task (aversive and neutral stimuli)	Slowed eye-blink latencies to startle probes	Systolic ↑ Diastolic ↑	↑	7.5% CO_2 challenge might reduce the speed and magnitude of startle responses
Attwood et al. (2015)	↑	↑ negative affect ↓ positive affect	Face identification task (ethnicity)	Lower identification accuracy	Systolic ↑ Diastolic X	↑	7.5% CO_2 challenge might impair facial identification accuracy (memory testing) but does not lead to false identification
Button et al. (2016)	↑	-	Social evaluation learning task	Increased errors in learning other-referential rules. No	Systolic ↑ Diastolic X	↑	7.5% CO_2 challenge might impair working memory and thus reducing accuracy

Authors	Subjective		Cognitive		Objective		Notes
	Anxiety	Mood	Task	Behaviour	BP	HR	
			(self-life, self-dislike, other-like, other-dislike)	gas effects on self-related rules			
Attwood et al. (2017)	↑	↑ negative affect ↓ positive affect	Free viewing forced choice face task	Lower emotion accuracy, greater bias towards seeing angry over happiness	Systolic ↑ Diastolic X	↑	7.5% CO_2 challenge might result in impairment of emotion recognition and an interpretation bias of negative stimuli (i.e., angry)
Easey et al. (2018)	↑	↑ negative affect ↓ positive affect	Audio–visual matching task Visual binary categorisation task	Less hits for the matching task, slower reaction times in categorisation task	Systolic ↑ Diastolic ↑	↑	7.5% CO_2 challenge might negatively influence simple information processing irrespective of stimuli clarity (i.e., degraded, clear)
Gillan et al. (2019)	↑	-	Model-Free and Model-Based Planning Task	Adjusted responses in line with goal irrespective of gas effect, more frequent choice switch	-	↑	7.5% CO_2 challenge might not worsen or benefit goal-directed planning, but create a tendency to explore new options

Authors	Subjective		Cognitive		Objective		Notes
	Anxiety	Mood	Task	Behaviour	BP	HR	
Savulich et al. (2019)	-	↑ negative affect, fear, panic symptoms ↓ happiness	Affective Go/No-go (AGN) Spatial Working Memory (SWM)	AGN: slower latencies when responding to positive words and more omission errors for negative words SWM: more total errors and poorer heuristic search strategy	Systolic ↑	↑	7.5% CO_2 challenge might lead to poor cognitive flexibility and working memory
Attwood et al. (2021)	↑	↑ negative affect ↓ positive affect	Walking task	Slower walking speed, better body posture	Systolic ↑ Diastolic ↑	↑	7.5% CO_2 challenge might result in adjustments to locomotor behaviour (linked to vestibular system)

Note. ↑ indicates significant increase and ↓ indicates significant decrease. X denotes no significant difference.

Regarding attentional processing, Garner et al. (2011) conducted a study on the effects of gas condition using an antisaccade task, and reported that negative images were associated with a higher frequency of erroneous eye movements (i.e., threat prioritising). These findings suggest that a 7.5% CO_2 challenge is a reliable laboratory protocol for inducing anxiety and can be used to test anxiety-related biases without the requirement for clinical samples.

1.4.2. Psychosocial Models

1.4.2.1. Socially Evaluative Threat in Psychosocial Models

Socially evaluative threat (SET) is processed distinctly in people with SAD (Wong et al., 2020), which distinguishes it as a specific disorder. However, people without a formal diagnosis of social anxiety, or healthy individuals, also display anxious reactivity in situations involving social evaluation (Dickerson, 2008). Performance-related or public speaking scenarios are commonly used to induce anxiety, but other social scenarios such as singing challenges (Le et al., 2020) and blind date scenarios (Hartanto et al., 2014) have also been shown to be effective in inducing anxious reactivity. In quantifying these paradigms as anxiogenic, mainly subjective self-report measures of anxiety, cardiovascular measures including heart rate and blood pressure, and neuroendocrine activity such as cortisol levels are measured. The reasons underlying the induced anxiogenic response by a socially evaluative paradigm have been associated with a few factors, one of which is 'uncontrollable threats to the goal of maintaining the social self' ((Dickerson & Kemeny, 2004), p. 356). To support this notion, research has found that a Cold Pressor Task (CPT) with a socially evaluative component, in which participants immerse their hands in cold water while being watched and videotaped, was significantly more effective in inducing an anxious response compared to non-social versions of the test (Schwabe et al., 2008).

In the literature, socially evaluative paradigms are often referred to as *stress* paradigms. The relationship between stress and anxiety appears intricate. Stress is caused by real or perceived imminent threat, whereas anxiety starts before the event (i.e., anticipation) and persists thereafter. Anxiety involves a series of distinct physiological responses, cognitive evaluations, emotional states, and behavioural patterns. Both stress and anxiety are natural responses that help individuals cope with dangers in their surroundings. When this distinct series of response mechanisms becomes impaired, anxiety disorders occur and manifest along a spectrum (American Psychiatric Association, 2013; Bystritsky & Kronemyer, 2014; Daviu et al., 2019). The socially evaluative protocols were found to be responsive to SAD and panic patients, in which these protocols increased subjective anxiety and negative affect among people with SAD relative to healthy controls, although cortisol reactivity was less consistent (Garcia-Leal et al., 2005; Grace et al., 2022). The subsequent chapters will elaborate on two prevalent paradigms commonly used as socially evaluative anxiogenic protocols in the anxiety literature. These include the Trier Social Stress Test (TSST) (Kirschbaum et al., 1993), which is considered the most influential (Kudielka et al., 2007), and impromptu public speaking (Droppleman & McNair, 1971).

1.4.2.2. The Trier Social Stress Test

In a standard TSST protocol, participants would be asked to make an impromptu oral presentation (five minutes) after a brief task introduction and a preparation period (10 minutes), and subsequently perform a surprising mental arithmetic task (five minutes) in front of a panel of three judges (Kirschbaum et al., 1993). During the task, the judges would refrain from feedback or encouragement whilst the participants are made to believe that their performance would be recorded (Allen et al., 2017; Labuschagne et al., 2019). The TSST is postulated to exhibit its anxiogenic effects through the dual challenge of maintaining one’s self-presentation while performing a cognitively demanding task that is beyond the individual’s control. Empirical evidence suggests that the anxiogenic effects of TSST are comparatively greater than those elicited by other cognitive tasks, such as performing a math task in isolation or engaging in a socially evaluative CPT (Giles et al., 2014).

A variety of versions have been adopted until now, including a TSST that can be conducted as a group (Childs et al., 2006; Von Dawans et al., 2011), a placebo version of the TSST (Het et al., 2009), and versions that are less stressful to be tested on children (Yim et al., 2010). The TSST consistently increases anxious arousal when tested on healthy volunteers (Allen et al., 2014), although the neurophysiological and subjective responses do not correlate well (Frisch et al., 2015). Additionally, the ability of anxious reactivity to persist across multiple days of testing was dependent on the specific neurological system that was activated. For instance, Schommer et al. (2003) reported that the hypothalamic–pituitary–adrenal (HPA) related responses (i.e., cortisol) were more susceptible to habituation when tested across three different days. Table 3 summarises the key findings on anxiogenic reactivity for studies that utilised TSST.

1.4.2.3. Public Speaking Test

There is currently no established consensus regarding the protocol, such as a TSST, for public speaking paradigms (Osório et al., 2008). The initial application of a Public Speaking Test (PST) protocol as an anxiety-inducing model in testing anxiolytic drugs included several phases. These include a baseline phase wherein the subjects are at rest upon arrival at the laboratory, an anticipation phase wherein the task instructions are detailed to the subjects, an execution phase wherein the subjects deliver a talk in front of a video camera, which they believe would be analysed later by a psychologist, and finally a recovery period wherein the participants are at rest once again (McNair et al., 1982). Because there was no real audience present during the presentation (other than

Table 3

Summary of Findings of Studies That Utilised Anxiogenic Socially Evaluative Paradigms on Healthy Volunteers

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
(Kirschbaum et al., 1993)	TSST	In-person	*N* = 20 (within-subjects)	Physical saline injection (and no subsequent test)	Neuroendocrine activity↑ Cortisol (serum and saliva) ↑ Heart rate ↑	2-4-fold increases in salivary cortisol levels, elevated serum cortisol concentrations, heart rate during the presence of stressor
(Het et al., 2009)	TSST	In-person	*N* = 84 (42 per group)	Placebo version of the TSST which contains a free speech and a simple mental arithmetic task	Salivary cortisol ↑ Salivary alpha-amylase↑ Stress appraisal ↑	In experiment 2 (within-subjects), group difference in salivary alpha-amylase was comparable.
(Yim et al., 2010)	TSST	In-person	*N = 31*	NA	Salivary cortisol ↑ Negative affect ↑ Positive affect ↓	The aim was to compare TSST children version to TSST adult version. Only adult data is reported.
(Schommer et al., 2003)	TSST	In-person	*N* = 65	NA	Salivary cortisol ↑ Heart rate ↑ State anxiety ↑ State mood ↑	The participants were tested over three days. Anxious reactivity was habituated after first day. 1st testing findings are reported here.

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
(Hellhammer & Schubert, 2012)	TSST	In-person	*N = 260*	NA	Salivary cortisol ↑ Heart rate ↑ Perceived stress, anxiety, and insecurity ↑	The outcome measures were compared against baseline (contrasts).
(Vors et al., 2018)	TSST	In-person	*N = 9*	NA	Salivary cortisol ↑ Negative affect ↑ Positive affect ↓	The authors reported the qualitative data of TSST in single and group settings. Single setting is reported here.
(Chalmers et al., 2021)	TSST	In-person	*N* = 60	NA	ECG ↑ Heart rate ↑ Heart rate variability ↑	No screening for participants was reported.
(Droppleman & McNair, 1971)	SPST *A topic of choice*	In-person	*N = 12*	NA	Finger sweat prints ↑ Arousal rating ↑	Authors also tested the habituation effects of repeated SPST.
(McNair et al., 1982)	SPST *Five randomly selected, no emotional, non-personal topics*	In-person	*N = 121*	NA	Palmar sweating ↑ State anxiety, fatigue ↑	The sample was medicated in different doses of diazepam.
(Al'Absi et al., 1997)	PST *Three different topics on controversial subjects*	In-person	*N* = 52	NA	State anxiety ↑ Cortisol ↑ Heart rate ↑	When PST was compared to a math task, PST produced more homogenous anxiogenic responses.

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
(Feldman et al., 2004)	SPST *Argue for and against the use of animals for sport*	In-person	*N* = 43 (n = 21 for PST, n = 22 for control)	Control task (reading passages aloud)	Threat appraisal ↑ Heart rate ↑ (during anticipation) SBP ↑ DBP ↑	Authors suggest that anticipation is required for anxiogenic speech tasks.
(Garcia-Leal et al., 2005)	SPST	In-person	*N = 51*	NA	Salivary cortisol ↑ State anxiety ↑ Bodily symptoms (e.g., lethargic) ↑	Authors compared panic patients to healthy controls. Main effect (of time) is reported here.
(Kelly et al., 2007)	TSST	Virtual	*N* =274	(1) only the speech task in front of a virtual audience, (2) relax and to simply observe the virtual audience but were told that they would not be delivering the speech they had prepared (3) the standard TSST (in-person) but behind a one-way mirror (4) no instruction concerning a speech or math challenge	Salivary cortisol X Threat appraisal X	The findings suggest that a VR-based is not as anxiogenic as real-life TSST. VR-based TSST was comparable to imagined audience (behind one-way mirror). No screening for participants was reported.

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
(Jönsson et al., 2010)	TSST	Virtual (CAVE™ system)	*N = 10*	NA	Salivary cortisol ↑ Heart rate ↑	Authors suggest that effect sizes obtained during the virtual TSST were similar to those conducted in real-life.
(Wallergård et al., 2011)	TSST	Virtual (CAVE™ system)	*N* = 7	NA	ECG ↑ Heart rate ↑ Qualitative discussion	Participants perceived the virtual scenario realistic.
(Hawn et al., 2015)	TSST	Virtual (CAVE™ system)	*N* = 43 (sample size per group was not reported)	Control task in VR (viewing a virtual aquarium)	Salivary cortisol ↑ Heart rate X Blood pressure ↑ Distress ↑	Authors also compared virtual TSST to traditional TSST. Archival data were used for traditional TSST. Virtual TSST has comparable anxiogenic effect as traditional TSST.
(Shiban et al., 2016)	TSST	Virtual (monocular HMD)	*N* = 45 (n = 15 per group)	Real-life TSST	Salivary cortisol X Heart rate X Threat Appraisal ↑ Distress ↑	Suggests that TSST in-vivo was comparable to virtual TSST for most measures (except stress threat appraisal ratings). Authors also compared a third group (VR competitor), but

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
						group differences are not reported here.
(Kothgassner, Hlavacs, et al., 2016)	TSST	Virtual	*N* = 8 (n = 4 for TSST group)	NA	Salivary cortisol ↑ State Stress ↑	Authors also reported anxiogenic effects of Cyberball but it was not reported here.
(Zimmer, Buttlar, et al., 2019)	TSST	Virtual (Oculus Rift)	*N* = 93 (n = 29 for TSST VR, n = 22 for control task in VR, n = 21 for real-life TSST, n = 21 for real-life TSST (control)	(1) real-life TSST (2) real-life TSST (control) (3) control task in VR	Salivary cortisol ✓ Heart rate ✓ Skin conductance ✓ State Stress ✓	Reported group differences are for the in-vivo TSST (versus in-virtuo TSST). Authors also reported the group differences of a control task in VR and a virtual TSST.
(Zimmer, Wu, et al., 2019)	TSST	Virtual (Oculus Rift)	*N* = 50	NA (see Notes)	Salivary cortisol ↑ Heart rate ↑ State anxiety ↑	Authors essentially tested the influence of pre-exposure to a real-life setting. The time main effect is reported here.
(Kothgassner et al., 2019)	TSST	Virtual	*N* = 56	NA (see Notes)	Heart rate ↑ State stress, exhaustion, irritation, aggression, shame ↑ State Relaxation ↓	Authors essentially tested the influence of virtual/real social support. The time main effect is reported here.

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
					State Worry X	
(Kothgassner et al., 2021)	TSST	Virtual	*N* = 68 (n = 23 for TSST-VT, n = 22 for real-life TSST, n = 23 for placebo TSST)	(1) real-life TSST (2) placebo TSST (in VR, no social evaluation)	Salivary cortisol ✓ Heart rate ✓ State stress ✓	Findings compared to real-life TSST are reported here.
(Kotlyar et al., 2008)	PST *Defending themselves from being falsely accused of shoplifting*	Speech task in VR, math task outside	*N* = 12	NA	Salivary cortisol X Heart rate ↑ Blood pressure ↑	A math task (as a positive control condition) was performed outside the VR environment. Only the PST is reported here.
(Kothgassner, Felnhofer, et al., 2016)	PST (audience size 20) *an integrated display to watch the standardized presentation slides*	Virtual	N = 66 (n = 22 per group)	(1) real-life PST (2) control PST (in VR, no social evaluation)	Salivary cortisol ✓ Heart rate ✓ ECG ✓ State anxiety ✓	Authors essentially tested the habituation effects of repeated virtual public speaking task. These findings are not reported here.
(Harvie et al., 2021)	iTSST	Online	N =104 (n = 50 for iTSST, n = 54 for iTSST placebo)	iTSST placebo	Smartphone- based PPG ↑ State stress and anxiety↑	Significant elevations in heart rate and self-reported stress and anxiety to the iTSST procedures compared to placebo iTSST

Author(s)	Anxiogenic Paradigm	Version (Reference Group)	Sample Characteristics	Compared Group	Measured Variables	Notes
(Eagle et al., 2021)	iTSST	Online	*N* = 50	NA	ECG (self-administered)↑ State stress ↑ State relaxation ↑	-
(Gunnar et al., 2021)	iTSST	Online	N = 68 (15-16 years old)	NA	Salivary cortisol ↑ State stress ↑	The sample tested was adolescents aged between 15-16 years old.
(DuPont et al., 2022)	iTSST *A job interview (visit 1), and introducing themselves to a new class of 20 students (visit 2)*	Online	*N* = 99 (n = 49 for iTSST, n = 50 for control)	Control iTSST (easier versions of the tasks with a single, friendly researcher)	Heart rate ↑ Blood pressure ↑ State anxiety, hostility, negativity, depression ↑ State calmness, positivity, well-being ↑ State vigour X	Authors also tested the anxious reactivity during a second visit, these are not reported here.

Note. TSST = Trier Social Stress Test. SPST = Simulated Public Speaking Test. PST = Public Speaking Task. iTSST = internet-delivered Trier Social Stress Test. VR = Virtual Reality. ECG = Electrocardiogram. PPG = Photoplethysmography. If no screening is reported, it has been mentioned in the table. The table compares the ‘Version’ column to the ‘Compared Group’ column (when applicable). ↑ indicates significant increase and ↓ indicates significant decrease. X indicates no significant difference. ✓ indicates comparable effects (only for the real life and virtual paradigm comparisons).

two researchers), the above-described protocol is commonly referred to as simulated public speaking. Later, versions with a real-life audience of varying sizes during an impromptu speech task have been employed as an anxiogenic model (Al'Absi et al., 1997; Feldman et al., 2004). The speech paradigms with a relatively large size of audience provoked more anxious arousal among healthy volunteers relative to simulated variants when a video was recorded and two researchers were included (Zuardi et al., 2013). This suggests that an increased size of a real audience may further enhance the anxiogenic reactivity of the test. In addition, because threat appraisal is necessary to be generated in the stress-anxiety continuum, an anticipation period is suggested to be necessary when designing impromptu anxiety-inducing speech paradigms (Feldman et al., 2004; Zuardi et al., 2013). The data recorded in testing public speaking paradigms was similar to TSST, including subjective, cardiovascular and behavioural responses that are recorded throughout the task multiple times (Garcia-Leal et al., 2014). Typically, a PST triggered significant anxiety-related responses, peaking during the anticipation phase and just before the actual performance (Al'Absi et al., 1997; Garcia-Leal et al., 2005). In addition, when compared to control versions of the task such as reading passages aloud, these anxiogenic reactions were also evident for speech paradigms (Feldman et al., 2004). For a comprehensive overview of the outcomes associated with speech paradigms, refer to Table 3.

1.4.3. Digital Psychosocial Models

Real life speech paradigms, as described earlier, present several challenges for experimental laboratory research. For instance, conducting studies in naturalistic social settings is a logistical challenge, resulting in increased cost (i.e., actor hiring) and time investment. In addition, ensuring that confederates exhibit standardised emotional responses throughout the protocol may not be feasible, which might confound the data findings (i.e., emotion contagion) (Buchanan et al., 2012).

Integrating technological advancements into this field represents a practical solution to overcome such difficulties (Freeman et al., 2017). This strategy has become more relevant since the COVID-19 pandemic and associated lockdowns which had temporarily paused laboratory research (Kirschbaum, 2021; Pfeifer et al., 2021; Wiederhold, 2021). Researchers have already taken advantage of virtual and online platforms to test socially evaluative paradigms. In the next chapters, I will detail these technologies and will provide empirical evidence in testing the anxiogenic paradigms in virtual and online platforms.

1.4.3.1. Virtual Reality Based Socially Evaluative Paradigms

The application of Virtual Reality (VR) into mental health began with the treatment of agoraphobia (North et al., 1996). Since then, research into VR in psychology literature has witnessed a dramatic rise, especially during the last decade (Rizzo & Koenig, 2017).

VR offers immersive computer-generated worlds, presented via a head mounted display, that fully replace sensory experiences with digitally created ones, where users view a complete stereoscopic visual field (Blascovich et al., 2002; Rizzo & Koenig, 2017). It is a novel technological tool that can simulate real-life social scenarios while preserving experimental rigour and control (Kothgassner & Felnhofer, 2020; Parsons, 2015; Slater & Sanchez-Vives, 2016). Developing anxiogenic virtual paradigms may have various advantages, including the ability to control confounding factors (e.g., confederate behaviour), manipulate environment variables as required, and standardise social interaction scenarios (Gaggioli, 2001).

In VR research, it has been found that immersive virtual scenes can elicit intended emotional arousal, regardless of whether the scenario is positive (e.g., joy) or negative (e.g., anger, anxiety, sadness) (Felnhofer et al., 2015). Further, Martens et al. (2019) tested the anxiogenic effects of a behavioural stressful scenario in VR (i.e., stepping off from a tall building), and reported heightened objective and subjective indices of arousal compared to a control scenario (i.e., stepping out of an elevator to the third floor). Interestingly, Montero-López et al. (2016) reported that a TSST protocol presented in a flat screen was more likely to induce anxiety than its virtual counterpart, however, the virtual device used in their study had a relatively small field of vision (40°) that might have limited a successful immersion effect. Recently, immersive 360-degree pre-recorded videos are utilised in VR, testing the cognitive mechanisms of social anxiety such as attention and avoidance in more realistic contexts (Rubin et al., 2020; Rubin et al., 2022). However, no research exists that has investigated naturalistic 360-degree socially evaluative virtual scenes in testing anxiogenic responses.

The extensive literature on exploring the anxiogenic effects of immersive socially evaluative paradigms has primarily utilised cartoon-like avatars rather than photorealistic 360-degree technology. Previous studies in this area have typically involved comparisons of virtual versions with real-life versions of these paradigms, as well as control protocols conducted in VR. According to a recent review article (Helminen et al., 2019), although VR has advantages in eliciting cortisol reactivity relative to control tasks that were also conducted in VR, its effectiveness may not be as potent as that of a real-life paradigm. Further, the produced anxiogenic responses were more susceptible to habituate in a VR-based TSST relative to a real-life one (Jönsson et al., 2010; Kothgassner et al., 2021). Although there is no review article at the moment regarding the cardiovascular effects of VR-based protocols, some individual publications have reported a less consistent agreement in anxious responses when a virtual TSST protocol was compared to a control task in virtual environments (e.g., (Hawn et al., 2015)). However, an in-vivo TSST was observed to induce a significantly heightened heart rate compared to a control task in a real-life setting (Zimmer, Buttlar, et al., 2019). Table 3 summarises the anxiogenic effects of these protocols conducted in VR. Helminen et al. (2019) reported in their review article that the degree of immersion was a significant moderator in mitigating the anxiety-inducing effects of socially evaluative virtual protocols. This might be one way to replicate the anxious effects of socially evaluative protocols to closely mirror those experienced in real-life situations within virtual social environments. In the next chapter, I will explain the presence concept in virtual environments, which is related to immersion levels and the interest of the current thesis. I will provide empirical evidence on how the literature has established its link to anxious arousal for anxiogenic paradigms.

1.4.3.1.1. Presence in Virtual Environments

The mechanism through which emotional arousal is produced in VR was suggested to be related to the concept of presence. Given that this thesis utilises VR as part of its methodology, it is important to acknowledge the existing research on this topic. Presence refers to the extent to which an individual feels connected to or engaged with virtual stimuli or environments (Schubert et al., 2001; Slater, 1999). Greater immersion in VR has been argued to increase presence when coupled with the degree of emotional arousal experienced in a given virtual scenario (Diemer et al., 2015). However, the existing literature on the relationship between presence and anxious arousal in VR is not consistent. Some studies have reported significant correlations between presence and anxious reactivity in socially evaluative virtual protocols (Kothgassner, Hlavacs, et al., 2016), while others have found limited evidence of such correlations, with only a few aspects of presence being related to subjective anxious arousal (Felnhofer et al., 2014; Morina et al., 2014). This inconsistency might suggest that either presence and anxious arousal experienced during a speech paradigm are separate factors, or that the operational definition of presence in the VR literature should be revisited. Ling et al. (2014) conducted a meta-analysis on the relationship between self-reported presence and anxiety for virtual exposure therapy in the treatment of anxiety disorders. The findings revealed an overall significant association between the sense of presence and anxiety. However, intriguingly, the magnitude of this association varied among different anxiety disorders. For instance, the relationship between self-reported presence and anxiety during virtual exposure therapy yielded a large effect size in addressing fear of animals, while there was almost no effect observed for SAD. Further, stronger correlations were found in people with formal diagnoses of an anxiety disorder relative to non-clinical populations (Ling et al., 2014). Understanding the concept of presence in the context of VR-based studies is crucial, especially when the methodology involves exposing participants to anxiety-inducing stimuli. Presence can serve as a valuable tool to justify the use of equipment in such studies despite the current lack of clear direction on how the level of presence experienced in the VR environment precisely impacts participants' reactions and responses.

1.4.3.2. Online Socially Evaluative Paradigms

The establishment of online anxiogenic protocols has been significantly driven by the lockdowns that followed the COVID-19 pandemic. These protocols have emerged as a means for researchers to adapt and continue conducting anxiety research, despite the limitations imposed by pandemic-related restrictions (Kirschbaum, 2021; Pfeifer et al., 2021). In a typical online anxiogenic protocol, participants are tested using social communication platforms on the internet, such as Zoom or Skype. Commonly used socially evaluative paradigms in these protocols include the TSST (Eagle et al., 2021; Gunnar et al., 2021; Harvie et al., 2021), introducing oneself to new class (DuPont et al., 2022), or a getting-to-know-you task (Huneke et al., 2022), where a dummy audience is often added as part of the protocol. The existing online protocols have been reported to induce anxious arousal effectively in participants. The detailed findings and results summarised in Table 3. With the increasing integration of online communication into our daily lives and the growing use of digital platforms for therapeutic purposes in the field of anxiety disorders, it is important to examine the physiological, cognitive, and behavioural responses associated with anxiety within these platforms. This is also important in validating the use of such online protocols in line with established theoretical models of anxiety disorders.

1.5. How Can Digital Anxiogenic Paradigms Enhance Understanding of Social Anxiety?

As mentioned in earlier chapters, the recognition of SET is distinct for SAD and contributes to the persistence of the disorder by targeting cognitive processes (Wong et al., 2020). The empirical testing of the distinct processes during anxiogenic protocols for people with SAD has involved negative focused-attention, negative self-perceptions, and performance evaluations (Rapee & Abbott, 2007), strengthening confidence in the validity of cognitive theories of social anxiety (Clark & Wells, 1995; Rapee & Heimberg, 1997). Relevant to the methodology of the current thesis, the latest technology advancements and their application in the context of social anxiety are reviewed. In the literature, digital technologies are used for therapeutical purposes, such as VR-based exposure therapy, which was found to be as effective as in-vivo variants (Anderson et al., 2013; Bouchard et al., 2017). Smartphone-based applications, such as the 'Challenger' app, have also been employed for SAD, involving small challenges in everyday life, including exposure exercises (Boettcher et al., 2012; Boettcher et al., 2013). Further, VR has been suggested as a reliable clinical diagnostic tool for SAD, with studies testing individuals with social anxiety on their cognitive and behavioural responses during virtual train and waiting room scenarios (Dechant et al., 2017). Additionally, VR has been utilised as a training tool to enhance public speaking efficacy (Frisby et al., 2020). As can be seen, the applications of digital technologies in the social anxiety context are wide and innovative. To understand better the validity and applicability of the aforementioned processes, an initial and informative step is to model anxiogenic responses within standardised socially evaluative paradigms using digital technologies.

To investigate the specificity of generated anxious arousal to SAD, research has been conducted to compare people with clinical or subclinical social anxiety to control groups, tested on subjective and objective anxious arousal during virtual or internet delivered social interactions. Virtual paradigms led to significant increases in subjective anxious arousal for people with SAD compared to controls (Felnhofer et al., 2014; Owens & Beidel, 2015), and relative to other anxiety-related disorders such as the post-traumatic stress disorder (Roelofs et al., 2009). However, the produced anxiogenic effects were not as efficient as real-life social scenarios among socially anxious groups (Owens & Beidel, 2015). In terms of internet-delivered paradigms, Huneke et al. (2022) examined social anxiety symptoms within an internet-delivered get-to-know-you task, reporting that trait social anxiety symptoms at baseline predicted increased anxiety during the social interaction task. The cardiovascular effects of online anxiogenic platforms tested on samples with social anxiety are yet to be investigated.

1.6. The Present Thesis

This literature review placed significant emphasis on cognitive social anxiety theories and their corresponding empirical studies, paying particular attention to methodological limitations. Additionally, the anxiogenic paradigms utilised in the current thesis were detailed, and their relevance to SAD was discussed. This comprehensive review identified gaps in the existing research and highlighted potential areas for improvement. These gaps include a lack of sufficient evidence regarding the effectiveness of VR-based socially evaluative paradigms in generating anxiety. Additionally, there is a paucity of studies investigating how online social communications may impact biased threat processing among social anxiety populations. This review underscores the need to address the methodological limitations of digital platforms in anxiety research. This thesis aims to utilise more ecologically valid and theory-based socially evaluative paradigms to advance our understanding of digital anxiogenic protocols and the manifestation of cognitive mechanisms underlying SAD within these paradigms.

Study 1 (Chapter 2) investigated a potential integration of a pharmacological challenge (7.5% CO_2) within a virtual socially evaluative threat scenario (i.e., public speaking) to generate subjective and objective anxious arousal. The study also explored how this integration would translate into the key maintenance mechanisms of SAD, such as anticipatory processing and performance evaluations.

In Study 2 (Chapter 3), a novel socially evaluative naturalistic protocol was developed and tested as an anxiogenic paradigm. The study also aimed to investigate the relevance of this newly developed paradigm to situational and trait social anxiety. By exploring the potential relevance of this novel paradigm to SAD, the study aimed to provide a more ecologically valid method for studying the cognitive mechanisms underlying social anxiety. In addition, this study investigated the potential for anxious arousal to habituate during a real-life socially evaluative scenario, following exposure to our naturalistic virtual paradigm.

Study 3 (Chapter 4) aimed to investigate how social anxiety may manifest in online communication platforms based on its cognitive theories. We developed an easy-to-follow protocol and tested the effects of camera manipulation (speaker camera versus audience camera) on subjective anxious arousal, as well as the key maintaining mechanisms of social anxiety (e.g., performance evaluations) for a subclinical social anxiety sample.

In summary, this thesis makes valuable contributions to the existing literature by introducing innovative digital paradigms for socially evaluative tasks, accompanied by robust protocols. This thesis also recognises the critical and timely role of integrating technology into the field of mental health, particularly in the context of SAD.

Chapter 2 – Evaluating the CO_2 Experimental Model of Anxiety within a Socially Evaluative Virtual Reality Paradigm

Abstract

Social Anxiety Disorder (SAD) is marked by anxious feelings and hyperarousal before, during, and after social situations. People with SAD tend to have cognitive biases in how they perceive themselves and others in social encounters, and these biases contribute to the prognosis severity of the disorder. Developing reliable, valid 'experimental models' that elicit the behavioural and physiological characteristics of social anxiety will help evaluate and refine new therapeutic interventions for social anxiety. Research has shown that inhalation of 7.5% carbon dioxide (CO_2) for 20 minutes induces subjective anxiety and the somatic symptoms of anxiety. The objective of this study was to develop a new experimental model of social anxiety that combines the CO_2 model with concurrent exposure to social environments via Virtual Reality (VR). Two groups of participants were given *either* air enriched with 7.5% CO_2 or regular room air, while a control group also received regular room air. All three groups rehearsed and performed a short talk in a virtual lecture room, with the first two groups presenting in the presence of a virtual audience, and the control group presenting in an empty virtual room (N = 93, n_{group} = 31). We found that giving a talk under the influence of CO_2 gas resulted in heightened subjective and objective anxious arousal. Additionally, this group of participants engaged in more frequent anticipatory ruminations and reported more negative evaluations of their performance. However, external observers rated all groups' performances as equal. These results suggest that combining the CO_2 gas mixture with a public speaking task could be a useful tool for investigating SAD in laboratory settings and could shed light on theories and cognitive mechanisms of the disorder.

Keywords: social anxiety, CO_2 challenge, Virtual Reality, experimental model

Introduction

Social Anxiety Disorder (SAD) is characterised by excessive fear and anxiety prior to, during, and after social or performance-based situations, wherein individuals may face the possibility of scrutiny by others (American Psychiatric Association, 2013). People with SAD hold a core fear of negative evaluation through which they believe their interactions in social settings will be perceived negatively, leading to feelings of humiliation, rejection, or embarrassment (Heimberg, Hofmann, et al., 2014). SAD is associated with cognitive biases in how people view themselves and others before, during, and after social encounters (Clark, 2001; Hofmann, 2007). These biases include, but are not limited to, an increased self-focus into one's cognitions and physical appearance, which may lead to an increase in anxious symptomology (Clark & Wells, 1995). Further, people with social anxiety tend to adopt specific scanning during social interactions, being vigilant, avoidant or vigilant/avoidant of potential social threat cues in their external environment (e.g., audience faces) (Heimberg et al., 2010; Schultz & Heimberg, 2008). Since more cognitive resources are allocated towards the scanning of internal and external cues, individuals with SAD may experience poor performance (Cheng et al., 2017; Norton & Hope, 2001; Stopa & Clark, 1993; Voncken et al., 2008), especially for demanding tasks (Daly et al., 1989; MacLeod & Mathews, 1991). However, some studies failed to find evidence of actual performance deficits in people with SAD when compared to healthy controls (Rapee & Lim, 1992; Strahan & Conger, 1998). A consistent finding within the existing body of research is that people with social anxiety *perceive* their performance more poorly relative to non-anxious groups (Brozovich & Heimberg, 2011; Cheng et al., 2017; Perini et al., 2006; Spurr & Stopa, 2003) and when compared to external observer ratings of participant performance (Alden & Wallace, 1995; Clark & Arkowitz, 1975; Gavric et al., 2017; Rapee & Lim, 1992; Stopa & Clark, 1993; Voncken & Bögels, 2008). In addition, SAD diagnosis is positively associated with negative ruminations prior to social interactions, commonly referred to as anticipatory processing (Penney & Abbott, 2014; Wong, 2016). This preoccupation with negative thoughts may impair an individual's ability to focus effectively on a social situation, potentially exacerbating anxiety symptoms during social encounters (Vassilopoulos, 2004).

Experimentally induced anxiety in healthy volunteers under laboratory settings can provide insights into the nature of psychiatric illnesses (Baldwin & Abou-Aisha, 2019; Baldwin et al., 2017). Psychosocial anxiogenic challenges often involve performing a short speech in the presence of a socially evaluative stimulus (Labuschagne et al., 2019; Osório et al., 2008). Public speaking scenarios where participants are asked to deliver an impromptu short speech in front of a video camera and experimenters (Droppleman & McNair, 1971) and to a real audience (Al'Absi et al., 1997; Feldman et al., 2004), or to simulate a job interview protocol as the applicant (known as the TSST) (Kirschbaum et al., 1993), have been well-established as acute anxiogenic laboratory protocols when tested on healthy individuals. Empirical work has confirmed that psychosocial challenges can worsen affective states (Allen et al., 2014) and increase subjective anxious arousal (Chalmers et al., 2021; Schommer et al., 2003), although cardiovascular responses (i.e., heart rate) have provided less consistent data (cf. (Feldman et al., 2004; Kotlyar et al., 2008)). Further, the use of Virtual Reality (VR) technology has enabled the translation of psychosocial protocols to more tightly controlled laboratory settings, allowing the delivery of social evaluative stimuli in a standardised and reproducible manner (Fallon et al., 2016; Kothgassner & Felnhofer, 2020; Parsons, 2015; Slater & Sanchez-Vives, 2016). Several studies have developed virtual adaptations of psychosocial protocols and have demonstrated similar levels of anxious reactivity between virtual social environments and real-life social scenarios (Kothgassner, Felnhofer, et al., 2016; Kothgassner et al., 2021; Zimmer, Buttlar, et al., 2019). However, a recent meta-analysis concluded that the magnitude of anxiety induced via virtual paradigms might not be as strong as that induced by real-life socially evaluative protocols (Helminen et al., 2019).

The effects of established psychological challenges based on observable social performance may be improved by combining them with other anxiogenic challenges (e.g., physiological, pharmacological). A pharmacological experimental protocol which involves inhalation of carbon dioxide (CO_2)-enriched air in healthy volunteers has been shown safely and robustly to evoke subjective and autonomic responses which mimic anxious states (Bailey et al., 2005). A broad range of anxiety disorders can be explored through inhalation of varying concentrations of CO_2. A higher CO_2 dose (e.g., 35%) triggers symptomology akin to panic disorder (Cosci et al., 2019; Valdivia-Salas et al., 2014; Van den Hout & Griez, 1984), while lower doses (ranging from 5% to 8%) produce symptomology similar to GAD (Bailey et al., 2005; Bailey, Kendrick, et al., 2007; Poma et al., 2005). Particularly, the inhalation of 7.5% CO_2 for 20 minutes was found to increase heart rate and blood pressure levels, and create subjective anxious states such as worry and fear, while reducing positive mood (Bailey et al., 2006; Bailey, Phillips, et al., 2007; Bailey et al., 2005). These short-lived effects have an early onset (two to four minutes after inhalation begins) and continue during the inhalation period (Bailey et al., 2005). 7.5% CO_2 inhalation for 20 minutes has been shown to alter a range of cognitive and emotional processes that are associated with anxiety disorders. Those include prioritising the threat-related stimuli and hypervigilant attentional patterns within computerised paradigms (Garner et al., 2011; Garner et al., 2012), and impairing task performance (Diaper, Nutt, et al., 2012). The 7.5% CO_2 challenge can also increase the tendency to interpret subtle or ambiguous cues negatively (e.g., video-clips) (Cooper et al., 2013) (See Section 1.4.1. for more details). Therefore, the capacity for a 7.5% CO_2 challenge to induce cognitive biases akin to anxiety disorders, along with the observed alterations in physiology and subjective states, can verify its use as an anxiety model within the broad range of the spectrum. However, limited research has explored the effects of the CO_2

challenge within the framework of social evaluative threat. That is, only three studies (Attwood et al., 2017; Cooper et al., 2013; Cooper et al., 2011) utilised either computerised face stimuli or observations of social interactions in which participants were not directly involved, none of which constituted direct or natural socially evaluative interactions.

People with SAD typically experience fear of negative evaluations during social interactions. It is, therefore, not unexpected that public speaking tasks have been identified as particularly relevant to this condition, often triggering heightened anxiety responses (Rapee & Abbott, 2007; Roelofs et al., 2009; Stopa & Clark, 1993). The theories of information processing biases into social anxiety emphasises a simultaneous processing of internal and external stimuli at an attentional and interpretational level during social interactions (Amir & Bomyea, 2010; Schultz & Heimberg, 2008). Research supports the hypothesis that people high in social anxiety interpret ambiguous social situations more negatively in valence than nonclinical controls (Stopa & Clark, 2000) and compared to people with dispositional anxiety (Amir, Beard, & Przeworski, 2005; Chen, Short, et al., 2020; Huppert et al., 2007). The internal attentional processing of the self for socially anxious groups involves monitoring themselves in a detailed manner as opposed to the features or aspects of the surrounding environment, resulting in heightened anxiety reactivity (Bögels & Mansell, 2004). This self-focused attention was suggested to be casually involved in social anxiety symptomology (Bögels & Lamers, 2002; Norton & Abbott, 2016; Zou et al., 2007). For instance, people with SAD were more likely to feel greater subjective anxiety and have negative thoughts or beliefs about the outcome of social situations when they are given information that their heart rate is increasing (even when it is not true) than when they are informed that their heart rate is decreasing (Wells & Papageorgiou, 2001).

The widely recognised ability of CO_2 administration to induce anxiety by targeting internal cues, such as increased heart rate, could lead to impaired threat processing, also when faced with social interactions. Integrating a socially evaluative proxy with the CO_2 challenge within a VR environment that replicates real-world social situations has the potential to create robust laboratory models of social anxiety, due to the above-mentioned theoretical and empirical grounds of SAD during social encounters. Successfully implementing this combination would facilitate a thorough understanding of the disorder and lead to the development of more tailored and precise treatment strategies.

We designed a study to investigate whether the augmentation of the 7.5% CO_2 challenge with a concurrent impromptu public speaking task performed in virtual environments elicits anxious arousal and demonstrates the key cognitive mechanisms of SAD (e.g., negative performance evaluations, anticipatory processing) under laboratory settings. Two groups inhaled *either* air enriched with 7.5% CO_2 or regular room air, and subsequently *both* rehearsed and performed a short talk in the presence of a virtual audience in a virtual lecture room, whilst an air-inhalation control group rehearsed and performed in an empty virtual environment (no audience). The participants' subjective and objective anxiety levels were measured throughout the experimental task, and negative self-evaluative thoughts were measured in the aftermath of the experimental task. We hypothesised that when performing in the presence of the virtual audience, people who had been administered 7.5% CO_2 would report heightened self-reported anxiety levels and exhibit increased heart rate compared to those who had inhaled normal room air, and the magnitude of the increase would be dependent on the phase of the task, with a peak difference just before delivering the talk, relative to the time when they initiated the preparation phase. This expectation was based on previous work that utilised anxiogenic socially evaluative paradigms (Kothgassner, Hlavacs, et al., 2016; Zimmer, Buttlar, et al., 2019). We also investigated whether inhaling CO_2 and delivering the subsequent speech task to a virtual audience would lead to the highest levels of negative self-evaluative thoughts on performance, relative to the other groups, from both the participants' view and an independent observer's rating.

The following analyses were conducted in an exploratory manner because our project utilised a novel digital anxiogenic paradigm that also involved a pharmacological challenge. As such, formulating a directional hypothesis was not feasible. Nonetheless, we aimed to report these variables to provide a comprehensive understanding of the relevance of this novel paradigm to social anxiety. We examined how the levels of anticipatory processing might vary across groups as well as the presence reported in the virtual paradigm. The examination of presence is crucial for our anxiogenic virtual paradigm as presence has been identified as a prerequisite for activating emotions through perceptual cues (Diemer et al., 2015; Felnhofer et al., 2014). In addition, pre-post changes in the reported levels of positive and negative affect, panic symptomology, and anxiety sensitivity were examined across three groups. Finally, we examined participants' sentiments toward the virtual paradigm by analysing the frequency and polarity of valence data (negative, positive, neutral).

Method

The study was carried out between November 2019 and August 2022[1]. The University of Southampton Research Ethics Committee approved the study protocol (reference: 48138.A4). All participants signed an electronic informed consent form during the telephone-screening and a written informed consent form on the day of the experiment. The information sheet detailed the potential effects of the gas mixture (e.g.,

[1] Due to the COVID-19 pandemic, the recruitment had to be paused from March 2020 to September 2021.

pins and needles, shortness of breath), emphasising that people's reactivity to the stimulus may vary. Participants received either research credits or monetary compensation for time spent (a total of 36 research credits, or £20). We preregistered this study (25/05/2022): https://osf.io/fy8cr.

Participants and Exclusion Criteria

We advertised the study through the University of Southampton's student web portal (www.efolio.soton.ac.uk), on campus via physical posters, and on social media. Participants who were either native speakers or fluent in the English language were eligible to participate. We telephone-screened 162 potential participants (88 females, M_{age} = 22.78, SD_{age} = 5.43) for any of the following current or past psychiatric diagnoses using a truncated diagnostic interview based on DSM-IV criteria using the Mini International Neuropsychiatric Interview (MINI) (Sheehan et al., 1998): depression, mania, generalised anxiety, panic disorder, agoraphobia, social anxiety disorder (SAD), obsessive compulsive disorder (OCD), post-traumatic stress disorder (PTSD), and alcohol and/or substance abuse or dependence. In an attempt to recruit healthy volunteers, further exclusion criteria included being physically unfit (e.g., cardiovascular conditions, migraines), smoking, prescribed or recent medication use, pregnancy, hypertension (>140/90 mm Hg), recent use of recreational drugs, body mass index <18 or ⩾28 kg/m2), a long or recent COVID-19 diagnosis, and acute illness prior to the testing session. Appendix A contains the complete list of exclusion criteria.

Of those 162 screened participants, 50 participants did not meet the eligibility criteria (25 females, M_{age} = 23.34, SD_{age} = 7.67). Thirteen eligible participants did not attend on the experiment day (six females, M_{age} = 21.92, SD_{age} = 4.09)[2], and six participants who were assigned to the 7.5% CO_2 inhalation withdrew during the protocol (four females, M_{age} = 24.67, SD_{age} = 5.13). Hence, the final sample included in the analyses were 93 healthy participants (54 females, M_{age} = 22.47, SD_{age} = 4.07).

We randomly assigned participants to one of the three experimental groups using a computerised research randomiser (https://www.randomizer.org/), wherein a randomised set of 31 repetitions of the three conditions were generated prior to testing: a group who inhaled air enriched with 7.5% CO_2 and subsequently performed in front of a virtual audience (“CO_2_Audience”), and two groups who inhaled regular room air before performing either in front of a virtual audience (“Air_Audience”) or in an empty virtual lecture hall (“Air_NoAudience”).

[2] The experiment was disrupted by COVID-19-related circumstances, which had resulted in the loss of communication.

Power Analysis

We used the G*Power software version 3.1.to conduct a power analysis (Faul et al., 2007). Corresponding to our main hypothesis, we specified an *a priori* 3 (Group) x 6 (Time) within-between interaction with a medium effect size (Cohen's f = 0.25) at 80% power and 5% type I error probability. Considering the observed double dissociation effect in G*Power (i.e., a positive effect in one group versus a similar negative effect in the second group), we halved the effect size (Cohen's f = 0.125). The recommended sample size was 90. We recruited 93 participants.

Materials

Virtual Reality (VR) Headset and Scene Development

The VR equipment used was the Oculus Rift consumer version headset (Facebook Inc.), offering 110-degree of field view with 640×800 resolution per eye, which was running on a Dell Desktop computer with an Intel i7 processor (Windows 10 operating system). Participant response input was recorded using the Oculus Rift Bluetooth touch controller. As shown in Figure 2, a prefabricated 3D virtual university lecture hall was purchased from the Unity Asset Store (https://assetstore.unity.com/packages/3d/props/interior/university-classroom-86107). Seventy-two virtual avatars were generated using the Autodesk software (https://charactergenerator.autodesk.com/, Autodesk Inc.), and a 3D animation pack was applied to the static avatars (https://mocaponline.com/products/fbx-life-desk, MoCap Online). The animations implemented were short gestures (e.g., nodding, looking left/right, agreeing/disagreeing) that are relevant to the prominent behaviours of a real audience, and these were randomly looped across avatars. Our avatars were equal in gender with a diverse ethnic background, as these were previously noted as potential confounders during virtual social interactions (Menshikova et al., 2018). The avatars' facial expressions did not signpost any negative or positive social cues, but rather neutral social cues. A background sound effect of people chatting was played via the built-in Oculus Rift 3D positional audio to gain more ecological validity, purchased from https://www.soundsnap.com. The dynamic virtual scenario was developed using Visual Studio (version 15.9.38), and relevant data were stored in the Unity game engine software, version 5.6.6 (Unity Technologies, 2018).

All of the parameters for the virtual environment without an audience were identical, except that the virtual hall was non-populated and had no background sound effects (Figure 2, Panel D).

Medical Gas (7.5% CO_2)

Regular room air was enriched with 7.5% CO_2 (21% O_2, balance N_2) and administered using an oral-nasal face mask attached to a 500-litre cannister through a

Figure 2

An Illustration of Virtual Scenes Used in the Experiment

Note. (A) illustrates the Preparation phase, (B) illustrates the Speech phase in the presence of a virtual audience, (C) illustrates the time when the visual analogue scale (SUDS) was reported just before giving the speech, and (D) illustrates the non-populated virtual environment during the Preparation phase.

T-valve and tubing (BIOPAC Inc., https://www.biopac.com). Figure 3 demonstrates the technical equipment and experimental set-up. The laboratory lead delivered the relevant Health and Safety training to all experimenters prior to data collection. For safety reasons, the gas was administered under single blind conditions in which the experimenters were aware of the group allocation.

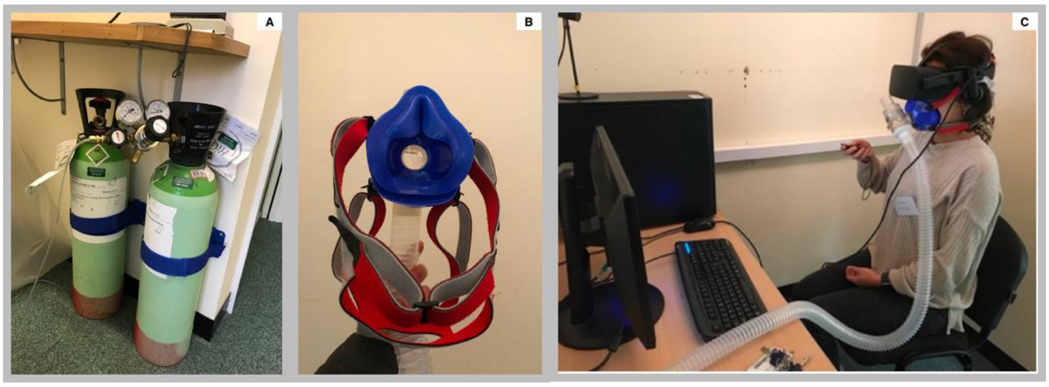
Measures

Baseline Measures

In addition to the demographical variables (age, gender and ethnicity), the following self-report measures were administered at the beginning of the study protocol during the testing day to allow characterisation of the experimental groups: Generalised

Figure 3

The Equipment and Experimental Setup



Note. The visual depicts the equipment used including CO_2 cannisters (A), oral-nasal face mask (B), and the experimental set up demonstared by the first author (C).

Anxiety Disorder Assessment (GAD-7) (Spitzer et al., 2006) to assess baseline trait anxiety symptom severity; Liebowitz Social Anxiety Scale - self report (LSAS-SR) (Liebowitz, 1987) to measure social anxiety symptom severity on the dimensions of experienced fear and avoidance; the Social Phobia Inventory (SPIN) (Connor et al., 2000) to measure social anxiety severity; and Personal Report of Communication Apprehension - public speaking sub scale (PRCA-24) (McCroskey, 2015) to assess communication apprehension for performing in public. All of these measures showed good psychometric properties (Cronbach's alphas > .89) (see Löwe et al. (2008) for the GAD-7; Fresco et al. (2001) for the LSAS-SR; Antony et al. (2006) for the SPIN; and McCroskey et al. (1985) for the PRCA-24).

Primary Outcome Measures

GAD-7$_{Modified}$

Participants completed GAD-7$_{Modified}$, a modified version of the seven-item GAD-7 (Spitzer et al., 2006) to measure state anxiety severity. Participants rated their level of anxiety in their response to the question, 'How often have you been bothered by the following problems *right now*?' on a scale ranging from 0 (*not at all)* to 3 (*nearly every minute*). GAD-7 has good psychometric properties (α= .89) in the non-clinical population as a broad anxiety severity measure (Löwe et al., 2008), and is responsive to treatment change with a medium-effect size (Cohen's d = .66) for SAD (Beard & Björgvinsson, 2014). The GAD-7$_{Modified}$ for our sample at the baseline showed good Cronbach's α of .80 (95% CI = .60 - .87, bootstrapped based on 1,000 samples).

Subjective Units of Distress (SUDS)

Participants rated their situational state anxiety in response to the question, 'How anxious do you feel right now?' on a visual analogue scale ranging from 0 (*not at all*) to

100 (*extremely anxious*) (Wolpe, 1990). SUDS as single-item measure is able to measure situational anxious arousal reliably (Davey et al., 2007), and is positively correlated with the State Trait Anxiety Inventory (STAI) (Spielberger et al., 1983), $r_{spearman} = .78$).

Heart rate

Continuous heart rate data were collected using publicly available Fitbit Charge 2 wrist-worn smart watches (Fitbit Inc., https://www.fitbit.com). Fitbit Charge 2 utilises photoplethysmography (PPG) signals as a non-invasive measurement method for health monitoring, measuring the volumetric changes of blood circulation using a green light source and a photodetector at the skin's surface (Castaneda et al., 2018). Previous research suggested that the heart rate accuracy estimations of Fitbit watches are within a respectable range, with a relative median error of less than 5% when compared to electrocardiographic monitoring (ECG) (Shcherbina et al., 2017). Every participant wore two Fitbit Charge 2 smart watches. Prior to testing, the smart watches were linked to two generic Fitbit accounts, and the corresponding information (i.e., wrist - left, right) was submitted per participant.

Other Measures

The following data were recorded at pre-test baseline and immediately after the experimental task: positive and negative affect using Positive and Negative Affect Scale (PANAS) (Watson et al., 1988), panic-like symptomology and the associated symptoms of autonomic arousal (e.g., shaking) using the Panic Symptom Inventory (PSI) (Clark & Hemsley, 1982), and the tendency to fear the symptoms of experienced anxiety using the Anxiety Sensitivity Index (ASI) (Reiss et al., 1986).

The following data were recorded only immediately after the experimental session: (a) Speech Performance Scale (SPS) (Rapee & Lim, 1992) to measure negative self-evaluative thoughts related to public speaking performance. SPS is a 17-item instrument with some reverse coded items (e.g., 'I had a clear voice/stuttered') and is rated on a scale of 0 (not at all) to 4 (very much). Higher scores represent better performance evaluations. The first author also completed SPS using transcribed audio recordings of participants to evaluate the task performance as an observer. The SPS scores as the outcome measure included nine items (1, 3, 4, 6, 7, 12, 15, 16, 17) of the original 17 to be able to match participant and observer ratings[3]. (b) Anticipatory Processing Questionnaire (APQ) to assess retrospectively the extent of anticipatory ruminations regarding the public speaking task (Vassilopoulos, 2004). Participants were instructed to recall their speech preparation process before their talk, and rated 17 items on a scale ranging from 0 (not at

[3] The SPS items that are excluded were related to non-verbal gestures of participants during the speech task that the experimenters were unable to rate (e.g., blushing) due to the VR fitting.

all) to 4 (very much) (Vassilopoulos et al., 2017). (c) Presence Questionnaire (PQ) (Witmer & Singer, 1998) to record the experience of being in the virtual environment where the responses were recorded on a visual analogue scale anchored between 0 (not at all) to 7 (completely). The PQ has 24 items addressing the aspects of realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance, and sounds and haptic experience during the VR experience. We excluded four items that corresponded to the haptic and sound subscales, since our virtual environment did not contain any sense of touch and not all experimental groups received a background sound (i.e., the empty virtual room). (d) One retrospective qualitative question on the thoughts, feelings, and sensations that participants experienced during the VR task was asked, with answers to be written with no minimum or maximum word count restrictions.

Experimental Protocol

Figure 4 depicts the summarised protocol. Upon pre-screening, healthy participants attended a single testing session at the laboratory. Participants were welcomed to the laboratory and the exclusion criteria were reassessed (see Appendix A for a detailed list). Participants put on two wrist-worn smart watches. The task procedure and how to operate the Bluetooth touch controller for the VR task were described, and the possible CO_2 effects were discussed with an emphasis on the right to withdraw at any point. The remainder of the protocol will be explained in five stages:

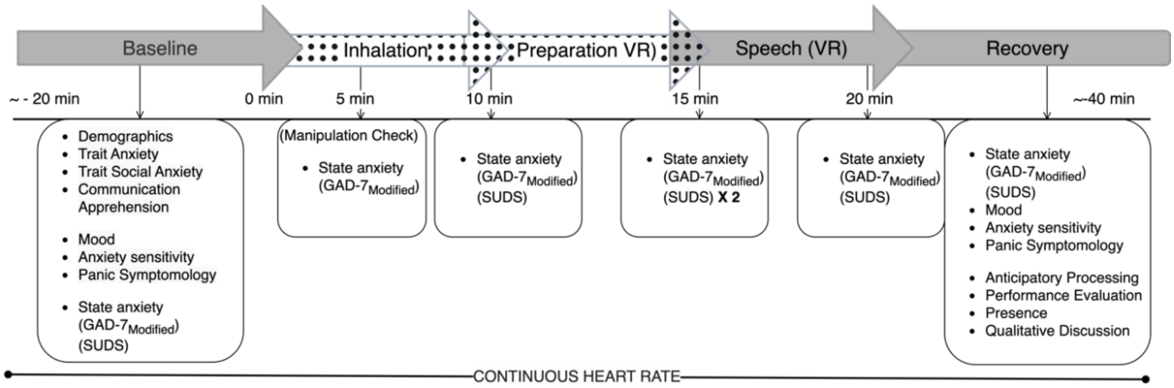
Baseline: Participants were acclimatised to the laboratory to ensure optimal arousal and completed the baseline and pre-task measures of the GAD-7, SPIN, LSAS, PRCA-24, PANAS, ASI, PSI, GAD-$7_{Modified}$, SUDS using the laboratory desktop computer. This phase took approximately 20 minutes to complete.

Inhalation: Participants put on the oral-nasal face mask (regardless of whether they were allocated to the CO_2 or the air groups) and breathed either air enriched with 7.5% CO_2 or regular room air for the next 10 minutes. Midway through the inhalation period (minute five), they completed a GAD-$7_{Modified}$ to record situational self-report anxiety as part of the manipulation check. Up until this phase, the questionnaire completions were done via a web-based platform (Qualtrics) using the desktop laboratory computer. During the final two minutes of the inhalation, we assisted participants to wear the VR headset whilst the gas/air was still being administered. If the VR setup was completed early, participants viewed an empty horizon in VR until the speech preparation period commenced.

Preparation: Participants rehearsed their upcoming talk in the virtual environments for five minutes whilst gas administration was continuing. They were either facing a lecture hall populated with a virtual audience of animated avatars or with no audience (depending on their group allocation). Participants proceeded in the experiment by themselves, guided by the written instructions on the virtual teleprompter. Before speech preparation,

Figure 4

A Simple Visualisation of the Experimental Protocol



Note. Dotted blocks represent the inhalation period (a total of 15 minutes).

their state anxiety was recorded (GAD-7_{Modified} and SUDS). Then, the teleprompter displayed the speech topic with some standardised prompts on which the participants could shape their talks. The teleprompter had a timer set to five minutes. The topic was 'The Future of Artificial Intelligence: The Harms and Benefits', and the prompts were 'dependency on machines', 'restricted work', 'unemployment', 'less room for errors', and 'AI in risky situations'. The topic was presumed to be non-personal and non-emotional, and no alternative options were provided. The timer started as soon as participants started the Preparation phase and was kept running while the questionnaires were being completed. This allowed for an exact 15-minute inhalation.

Speech: Participants were disconnected from the oral-nasal mask by removing the H-strap that was clipped to the mask. The teleprompter removed the prompts, and the timer was reset to another five minutes for the talk. The ambient spotlights were dimmed to draw attention to the speaker. In the avatar-populated virtual scenes, the audience head movements and gaze were shifted to the participant's location in the scene, the audience posture and movement became still, and the background sound effect was attenuated to achieve a more ecologically valid, comparable experience of delivering a talk to a real-life audience. Before initiating their talks, participants recorded their state anxiety via a GAD-7_{Modified} and SUDS before the spotlights were dimmed. A second SUDS recording was captured after the spotlights in the virtual scenes were dimmed. They then delivered five-minute talks, followed by state anxiety self-reports (GAD-7_{Modified} and SUDS), recorded once each.

Recovery: Participants were disconnected from the VR headset and completed the post-task self-report measures (GAD-7_{Modified}, SUDS, PANAS, ASI, PSI, SPS, APQ, PQ, brief qualitative discussion) on Qualtrics using the laboratory desktop computer. Participants verbally consented that they were fit for departure. All participants were contacted within

24 hours of the testing session to check whether any adverse effects might have occurred (e.g., headache).

Participants completed the VR task while standing (the *Preparation* and *Speech* phases), and they were seated during the rest of the phases of the experimental protocol. At least two researchers were involved in the recruitment process, and the participants were within accessible sight of the researchers during the process (although they remained in different rooms). Although located outside of the experiment room, the gas cylinders produced a hissing background sound during the CO_2 inhalation; therefore an identical, pre-recorded version of this noise was played for the air-inhalation groups. The participants' speech was audio recorded, and they had been made aware of this prior to the experiment.

Data Analytic Strategy

All statistical analyses were performed using R Software, version 4. 0.2. (R Core Team, 2022). All effects were reported as significant at $p < .05$ (after adjusting the significance values for follow-up statistics depending on the number of tests if required).

Demographical and baseline differences were analysed using one-way ANOVAs. We employed linear mixed-effects models using the package 'afex' (Singmann et al., 2022) to run our omnibus models. We assessed the change on self-reported state anxiety ($GAD\text{-}7_{Modified}$, SUDS) and heart rate, affect, anxiety sensitivity, and panic symptomology, with Time[4] and Group being entered as fixed effects and participants being entered as random effects (error term). The model took the form of:

State Anxiety ~ 1 + Time + Group + Time*Group + Error (ID/ Time)

We used afex (Singmann et al., 2022) to run a between-subjects model in which performance evaluations were factored into the participant and observer ratings, and their interaction.

We used the 'emmeans' package (Lenth et al., 2018) for the decomposition of the interaction effects. We probed the significant main effects via pairwise tests with customised consecutive contrasts. We adjusted the *p* values using the Bonferroni correction for follow-up pairwise tests. The statistical tests for which we had specific directional hypotheses were one-tailed to improve statistical power, and the rest were two-tailed.

We ran one-way ANOVAs to investigate the Group differences on exploratory outcome measures (anticipatory processing, VR presence). We reported partial eta

[4] The number of levels for the Time factor has differed for each main analysis, therefore they are specified in the Results section.

squared (η2p) for the omnibus models and Cohen's *d* ($(M2 – M1)/SD_{pooled}$) for the simple effects multiple comparisons, and for pairwise tests as the effect size measurement.

Heart Rate Data

The sampling frequency of the Fitbit Charge 2 ranges from five to 15 seconds, depending on the Fitbit itself. Data were gathered using the Fitbit manufacturers' Application Programming Interface (API). The Fitbit heart rate data (timestamps provided based on Network Time Protocol, GMT +1) were matched with the experimental task start and end time and date, which were manually recorded in seconds for each participant. We used TeamViewer (https://www.teamviewer.com/en/) to mirror the VR screen that participants were viewing onto another device and captured the exact start and end times per task stage.

Because the sampling frequency is determined by the Fitbit, we incorporated missing values (NAs) in the dataset at the one-second level and then smoothed the data with a rolling average, with a window size of two, that takes four true observations from each sides (two left, two right) into account, using the 'imputeTS' package in R (Moritz & Bartz-Beielstein, 2017) per participant and key event. We then aggregated the data over time periods that corresponded to five key events: Baseline, Inhalation, Preparation, Speech, Recovery. We averaged five-minute periods from each key event. We used the final five minutes for Baseline and Recovery phases, and minute three to seven (inclusive) for the Inhalation phase. We quantified these minutes because they were the least likely to be influenced by external confounding factors (e.g., equipment setup).

Due to a technical error, we failed to record data from both watches for 23 out of the 93 participants. In addition, n = 9 data points were recorded for only one watch. Therefore, we studied the agreement of the two smart watches on $N = 61$, running concordance class correlation (CCC) analyses (Lin, 1989) using the 'epiR' package (Stevenson et al., 2018). In line with the previous research, the strength of the agreement was interpreted based on the following: weak (CCC<.5), moderate (CCC = .5 - .7), and strong (CCC>.7) (Nelson & Allen, 2019). The analyses were computed on the rolling average of each Time phase (i.e., 'Baseline', 'Inhalation', 'Preparation', 'Speech', 'Recovery') recorded through two watches worn on different wrists. There was a strong measurement agreement between the two watches at Baseline (CCC = .970 95%CI [.951, .982]), at Inhalation, (CCC = .930 95%CI [.889, .956]), at Preparation (CCC = .802 95%CI [.691, .876]), at Speech (CCC = .889 95%CI [.823, .932]), and at Recovery (CCC = .853 95%CI [.768, .909]). Given strong agreements between two watches at all phases of the experiment, we felt confident to be able to add the datapoints from one watch (n = 9) which was missing from the second watch to run our main analysis. Therefore, the final data included $N = 70$ datapoints ($n_{CO2\_Audience} = 25$, $n_{Air\_Audience} = 24$, $n_{Air\_NoAudience} = 21$).

Sentiment Analysis

We ran a sentiment analysis on the brief qualitative discussion that the participants provided at the very end of the testing day, using the sentimentr package in R (Rinker, 2021). The package sentimentr contains 11,709 words from several dictionaries (Jockers-Rinker sentiment lexicon). Weighting is applied to each sentence to accommodate valence shifters, which can reverse, amplify, or reduce the impact of a word (Naldi, 2019). Sentences are classified for sentimental valence on a continuous scale ranging between ± 1. Our data cleaning strategy included lowering all letters, replacing symbols with letters (e.g., '1^{st}' to 'first'), extending the contractions (e.g., 'could not' instead of 'couldn't'), and checking for typos. To obtain sentiment data, we generated composite sentiment scores per sentence per participant using the base dictionary, and then averaged them across three Groups. The written text counts across the three Groups were almost equivalent ($n_{CO2\_Audience}$ = 1694, $n_{Air\_Audience}$ = 1946, $n_{Air\_NoAudience}$ = 1869).

Results

Group Characteristics

Table 4 presents the group characteristics for the demographical data and the inferential statistics for the baseline self-report measures. Briefly, all groups comprised of young adults who identified as white and did not differ in age, gender, or body mass index (BMI). All three groups reported low levels of trait anxiety and trait social anxiety, and had comparable, low degrees of communication apprehension. Participants in our recruiting before and after COVID-19 exhibited similar demographics and trait anxiety characteristics (See Appendix B).

CO_2 Manipulation Check and Gas Expectancy

We determined the effectiveness of the 7.5% CO_2 challenge by evaluating state anxious arousal using GAD-$7_{Modified}$ after five minutes of gas intake across Groups. Prior work has shown that a typical 20-minute breathing of CO_2 can lead to increased levels of anxious arousal (Bailey et al., 2006), with effects manifesting as early as five minutes into the inhalation period (Bailey et al., 2005). In the model, Group was entered as a factor and participants were coded as an error term. The findings suggested that the three groups significantly differed in their anxious arousal after five minutes of breathing, $F(2, 90)$ = 19.48, $p < .001$, η2p = .302. The pairwise t-tests suggested that the reported anxiety levels were comparable for the groups who had inhaled air ('Air_Audience', M = 1.10, SD = 1.35; 'Air_NoAudience', M=1.35, SD= 2.21, $t(90)$ = 0.26, p =.927, d = 0.14), but the Group who were administered CO_2 ('CO_2_Audience') reported the highest level of state anxious arousal (M=4.97, SD=3.95), which was significantly different from both of the air inhalation groups (ts > 5.21, ps < .001, ds> 1.12). This suggested that the CO_2 manipulation was successful. The inhalation expectancy (CO_2 or air) of groups, using

Table 4

Descriptive and Inferential Statistics of the Group Trait Characteristics

	Groups									
	CO_2_Audience			Air_Audience			Air_NoAudience			
	n	M	*SD*	n	M	*SD*	n	M	*SD*	Test
Gender	31			31			31			χ2 = 0, *p* >0.10
…Female	18	58%		18	58%		18	58%		
…Male	13	42%		13	42%		13	42%		
Age	31	23.45	4.15	31	22.13	4.16	31	21.84	3.63	*F*(2, 59.74) = 1.41, *p* = .252
Ethnicity	31			31			31			χ2 = 4.70, *p* >0.10
…White	20	65%		20	65%		21	68%		
…Black	0	0%		1	3%		0	0%		
…Asian	7	23%		7	23%		7	23%		
…Mixed	0	0%		0	0%		1	3%		
…Other	4	13%		3	10%		2	6%		
Body Mass Index (BMI)	31	22.53	2.46	31	22.39	2.78	31	22.86	2.59	*F*(2, 59.86) = 0.27, *p* = .775
GAD-7	31	2.97	2.93	31	2.55	2.49	31	2.61	3.56	*F*(2, 58.82) = 0.19, *p* = .824
SPIN	31	11.84	10.01	31	9.87	9.96	31	10.74	9.35	*F*(2, 59.94) = 0.30, *p* = .742
LSAS	31	27.97	21.35	31	24.90	20.34	31	25.42	15.17	*F*(2, 58.47) = 0.19, *p* = .823
PRCA-24	31	18.71	4.87	31	17.48	4.21	31	17.87	4.03	*F*(2, 59.65) = 0.57, *p* = .566
Heart rate (Arm Cuff Baseline)	25	77.7	8.94	24	77.5	10.36	21	77.9	9.36	*F*(2, 43.88) = 0.012, *p* = .988

Note. GAD-7 (Generalised Anxiety Disorder Assessment), SPIN (The Social Phobia Inventory), LSAS (Liebowitz Social Anxiety Scale), PRCA-24 (The Personal Report of Communication Apprehension). Degrees of freedom (df) were adjusted for not assuming equal variances among between-subjects groups.

Fisher's exact test (two-sided) for a 3 (Group) by 2 (Expectancy Accuracy, True/False) contingency table, indicated that gas allocation did not predict group differences on the expectancy accuracy, $p^a = .491$.

Main Analysis: Subjective Anxious Arousal

To investigate self-reported subjective anxious arousal during the virtual public speaking task, we ran two separate linear-mixed effects models on state anxiety (GAD-$7_{Modified}$ and SUDS), where factors were entered as fixed effects and participants were specified as random effects (error term).

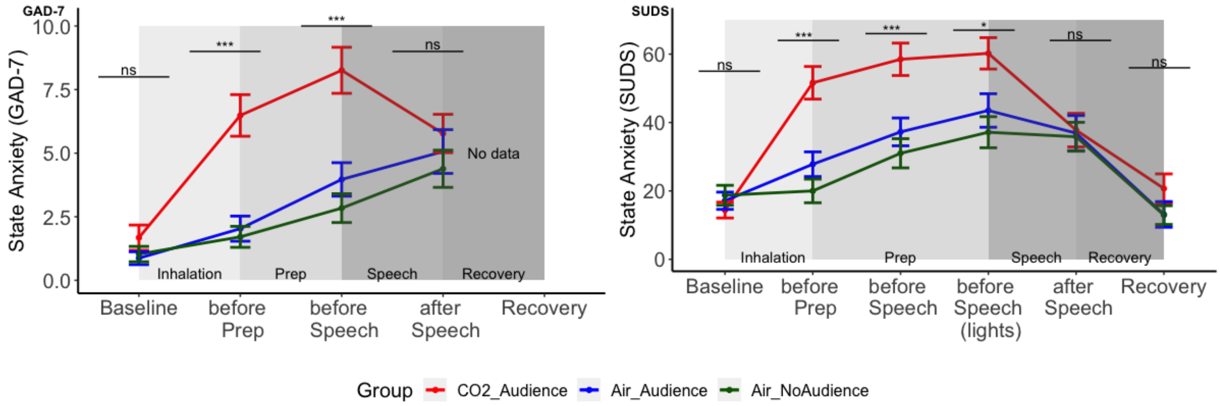
GAD-$7_{Modified}$

The factor levels were 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 4 (Time: Baseline, before Preparation, before Speech, after Speech). The test findings indicated that there was a significant main effect of Group, $F(2, 90) = 10.76$, $p < .001$, η2p = .193, and a significant main effect of Time, $F(2.45, 220.46) = 47.48$, $p < .001$, η2p = .345. The visual pattern (Figure 5, left panel) depicted an increase in situational anxiety levels till Speech, followed by returning to baseline levels post-speech. These effects were qualified by a significant interaction of Group*Time, $F(4.90, 220.46) = 8.20$, $p < .001$, η2p = .154, suggesting that the magnitude of the reported anxiety differed by the means of the group allocation, depending on the course of the experimental task. Breaking down the interaction effects, the Groups' level of self-reported state anxiety significantly differed before Preparation, $F(2, 90) = 19.72$, $p < .001$, η2p = .305, and before Speech, $F(2, 90) = 15.59$, $p < .001$, η2p = .257, whilst state anxiety levels of Group were comparable at Baseline, $F(2, 90) = 1.36$, $p = .262$, η2p = .029, and after Speech, $F(2, 90) = 0.784$, $p = .460$, η2p = .017.

Planned contrasts compared each consecutive Group before Preparation and before Speech. As observed in Figure 5 (left panel), Before Prep, the levels of situational anxiety were comparable in the absence or presence of the virtual audience, $t(90) = 0.380$, $p = .999$, $d = 0.13$ (cf. Air_Audience and Air_NoAudience); however, if the audience was present, the additive CO_2 effect led to significantly higher levels of state anxiety relative to regular room air effect, $t(90) = 5.24$, $p < .001$, $d = 1.18$ (cf. CO_2_Audience and Air_Audience). This pattern remained before Speech in which preparing for the public speaking task in the presence or absence of an audience resulted in comparable levels of anxiety under regular room air inhalation, $t(90) = 1.10$, $p = .546$, $d = 0.33$ (cf. Air_Audience and Air_NoAudience), whilst the CO_2 addition (versus regular room air) in the presence of a virtual audience led to greater levels of state anxiety, $t(90) = 4.19$, $p < .001$, $d = 0.97$ (cf. CO_2_Audience and Air_Audience). Table 5 presents the observed means and standard deviations, effect sizes, and increases/decreases in percent for the differences in GAD-$7_{Modified}$ over baseline levels.

Figure 5

Subjective Anxious Arousal by Group throughout the VR Task



Note. Error bars represent the standard error (SE). Refer to the Method section for the timeline of the events. ns = not significant. * = *p*< .05, ** = *p*<. 01, ***= *p*<.001.

SUDS

The factor levels were 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 6 (Time: Baseline, before Preparation, before Speech, before Speech (lights), after Speech, Recovery). The findings revealed a significant main effect of Group, $F(2, 90)$ = 6.14, p < .001, η2p = .120 and Time, $F(3.80, 342.40)$ = 60.28, p < .001, η2p = .401. Similar to the $\text{GAD-7}_{\text{Modified}}$, the subjective anxious arousal increased until Speech and then started to decrease till Recovery (Figure 5, right panel). Importantly, the two-way interaction effect was significant, $F(7.61, 324.40)$ = 6.94, p < .001, η2p = .134. Upon further probing of the interaction effect, the Groups' self-reported anxiety significantly differed before Preparation, $F(2, 90)$ = 17.04, p < .001, η2p = .275, before Speech, $F(2, 90)$ = 10.88, p < .001, η2p = .195, and before Speech after the lights were dimmed, $F(2, 90)$ = 19.72, p= .002, η2p = .126. State anxiety levels of Group remained comparable at Baseline, $F(2, 90)$ = 0.711, p = .494, η2p = .016, after Speech, $F(2, 90)$ = 0.041, p = .959, η2p = .001, and at Recovery, $F(2, 90)$ = 1.48, p = .232, η2p = .032.

Planned contrasts compared each consecutive Group before Preparation, before Speech, and before Speech when the lights were dimmed, on SUDS. As evident in Figure 5 (right panel), before Preparation, under regular air inhalation, state anxiety levels were comparable in the presence or absence of a virtual audience, $t(90)$ = 1.38, p =.340, d = 0.40 (cf. Air_Audience and Air_NoAudience). When a virtual audience was present, the CO_2 inhaled group reported higher degrees of state anxiety as opposed to the air inhaled group, $t(90)$ = 4.22, p <.001, d = 1.01 (cf. CO_2_Audience and Air_Audience). These observed effects indicated that the virtual audience presence resulted in similar subjective anxious arousal under air inhalation before Speech $t(90)$ = 1.01, p = .627, d = 0.27, and before Speech when the spotlights were dimmed $t(90)$ = 0.960, p = .679, d = 0.24 (cf.

Table 5

Observed Means and Standard Deviations, Effect Sizes, and Increases/Decreases in Percent for the Differences in Subjective Anxiety Over Baseline Levels

	GAD-7									SUDS								
	CO_2_Audience (n = 31)			Air_Audience (n = 31)			Air_NoAudience (n = 31)			CO_2_Audience (n = 31)			Air_Audience (n = 31)			Air_NoAudience (n = 31)		
	M (SD)	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%
Baseline	1.68 (2.26)	-	-	0.87 (1.41)	-	-	1.03 (1.68)	-	-	14.4 (12.9)	-	-	17.1 (14.0)	-	-	18.7 (16.2)	-	-
Before Prep	6.48 (4.55)	1.33	+74.07	2.03 (2.75)	0.53	+57.14	1.71 (2.30)	0.34	+39.77	51.6 (26.5)	1.78	+72.09	27.8 (20.1)	0.62	+38.49	20.0 (19.3)	0.07	+6.50
Before Speech	8.26 (5.04)	1.68	+79.81	3.97 (3.67)	1.11	+78.09	2.84 (3.15)	0.72	+63.73	58.5 (26.4)	2.12	+75.38	37.43 (22.7)	1.08	+54.24	31.0 (23.8)	0.60	+39.68
Before Speech (*lights*)	-	-	-	-	-	-	-	-	-	60.2 (25.5)	2.27	+76.08	43.5 (27.3)	1.22	+60.69	37.2 (25.3)	0.87	+49.73
After Speech	5.77 (4.19)	1.21	+70.94	5.06 (4.79)	1.19	+82.87	4.39 (4.07)	1.08	+76.49	37.8 (27.3)	1.09	+61.90	36.9 (28.6)	0.88	+53.77	35.89 (23.5)	0.85	+47.92
Recovery	-	-	-	-	-	-	-	-	-	20.7 (23.7)	0.33	+30.43	13.1 (20.9)	0.22	-30.53	12.9 (15.3)	0.37	-44.96

Note. + = increase, - = decrease. See Figure 4 for a summary of the protocol and time points. Effect size of *d* ($M2 - M1$)/SD_{pooled} is reported.

Air_Audience and Air_NoAudience). Conversely, if the Groups saw the virtual audience, preparing the talk under the CO_2 influence led to greater subjective anxious arousal as opposed to being under the regular air, at both before Speech *t(*90) = 3.44, *p* = .002, *d* = 0.86, and before Speech when the lights were dimmed *t(*90) = 2.52, *p* =.027, *d* = 0.63 (cf. CO_2_Audience and Air_Audience). Table 5 presents the observed means and standard deviations, effect sizes, and increases/decreases in percent for the differences in SUDS over baseline levels. Taken together, these findings on subjective anxious arousal for both GAD-$7_{Modified}$ and SUDS showed similar trends. Our data did not provide evidence on the anxiogenic effect of a virtual audience that could account for socially evaluative threat; however, it did support the prospective anxiogenic effect of our proposed paradigm. That is, the augmentation of the CO_2 inhalation and a socially evaluative threat that was delivered via a virtual audience can generate acutely induced subjective anxious arousal in healthy individuals during a public speaking performance, which recovers to near baseline levels once the anxiogenic task is completed.

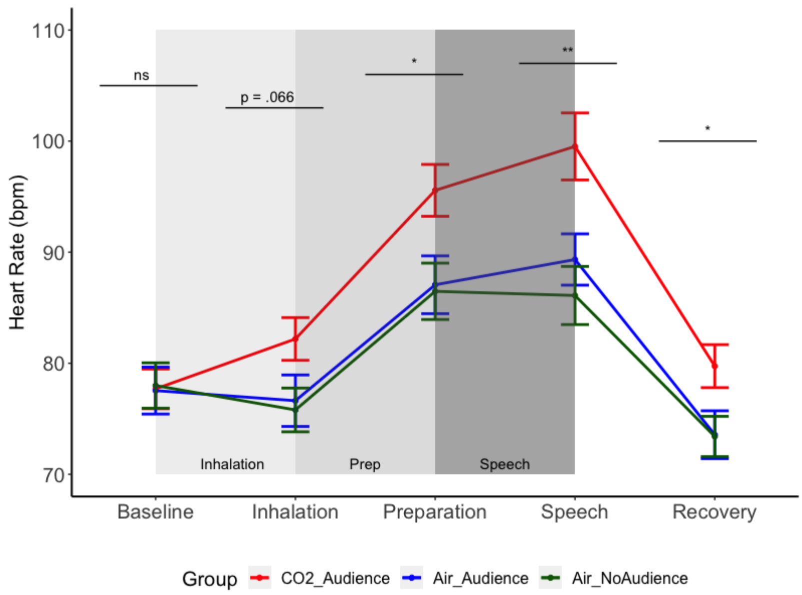
Main Analysis: Objective Anxious Arousal

To investigate the change in heart rate levels within our VR paradigm, a 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 5 (Time: ‘Baseline’, ‘Inhalation’, ‘Preparation’, ‘Speech’, ‘Recovery’) linear mixed-effects model was run, with participants being entered as random effects. There was a significant main effect of Group, *F*(2, 67) = 3.80, *p* =.027, η2p = .102 and Time, *F*(2.14, 143.17) = 108.63, *p* < .001, η2p = .619. Further, we detected a significant Group*Time interaction, *F*(4.27, 143.17) = 4.52, *p* = .001, η2p = .119, suggesting that the magnitude of the alterations in heart rate levels throughout the task depended on the Group allocation. Upon decomposing the two-way significant interaction effect, the Groups’ heart rate levels were comparable at Baseline, *F*(2, 67) = .013, *p* = .987, η2p < .001, and showed a trend at Inhalation, *F*(2, 67) = 2.83, *p* = .066, η2p = .078. The Groups’ heart rate levels significantly differed during Preparation, *F*(2, 67) = 4.28, *p* = .018, η2p = .113, Speech, *F*(2, 67) = 6.87, *p* = .002, η2p = .170, and at Recovery, *F*(2, 67) = 3.40, *p* = .039, η2p = .092.

Planned contrasts compared each consecutive Group at Preparation, Speech, and Recovery. As evident in Figure 6, physical reactivity was significantly higher when participants were confronted with a virtual audience while having been administered air enriched with 7.5% CO_2 as opposed to regular room air (cf. CO_2_Audience and Air_Audience) during Preparation, *t(*67) = 2.47, *p* =.032, *d* = 0.70, and Speech, *t(*67) = 2.75, *p* =.015, *d* = 0.76. At Recovery, physical reactivity levels remained equivalent with a trend toward significance, *t(*67) = 2.25, *p* =.056, Cohen’s *d* = 0.60. Under regular air inhalation, physical reactivity remained comparable either when a virtual audience were present or absent during Preparation, *t(*67) = 0.164, *p* =.999, *d* = 0.05; Speech, *t(*67) = 0.836, *p* =.812, *d* = 0.27, and at Recovery, *t(*67) = 0.056, *p* =.999, *d* = 0.02.

Figure 6

Objective Anxious Arousal by Group throughout the VR task



Note. Error bars represent the standard error (SE). The analysis was run on *N* = 70 datapoints ($n_{CO2\_Audience}$ = 25, $n_{Air\_Audience}$ = 24, $n_{Air\_NoAudience}$ = 21). Refer to the Method section for the timeline of the events. ns = not significant. * = $p< .05$, ** = $p<. 01$.

Table 6 presents the observed means and standard deviations, effect sizes, and increases/decreases in percent for the differences in heart rate over baseline levels.

To summarise, our data on physical reactivity suggested that when engaged with a virtual audience or in an empty virtual room, a public speaking performance generated similar levels of objective anxious arousal. However, when the virtual audience was present, participants performing in VR were able to produce greater physical reactivity under the influence of CO_2 as opposed to regular room air.

Other Analyses

Negative and Positive Affect

We ran two separate linear mixed-effects models on negative affect and positive affect, in which Group (3: CO_2_Audience, Air_Audience, Air_NoAudience) was entered as a factor of Time (2: Baseline/Pre, Recovery/Post) in the model. The main effect of Group was not significant for both positive and negative affect with a(*ps* > .056, *F*s< 3.00 η2ps < .063). The main effect of Time was significant on both negative and positive affect, in which the VR stress task resulted in decreased positive affect and increased negative affect irrespective of Group allocation (*ps* < .001, *F*s > .12.91, η2ps >.125). The Group*Time interaction was significant on both negative affect, *F*(2, 90) = 3.16, *p* = .047,

Table 6

Observed Means and Standard Deviations, Effect Sizes, and Increases/Decreases in Percent for the differences in Heart Rate Levels Over Baseline Levels

	CO_2_Audience (n = 25)			Air_Audience (n = 24)			Air_NoAudience (n = 21)		
	M (*SD*)	*d*	%	*M* (*SD*)	*d*	%	*M* (*SD*)	*d*	%
Baseline	77.7 (8.94)	-	-	77.5 (10.4)	-	-	78.0 (9.36)	-	-
Inhalation	82.2 (9.61)	0.48	+5.48	76.6 (11.4)	0.08	-1.17	75.8 (9.03)	0.24	-2.90
Prep	95.6 (11.7)	1.72	+18.73	87.1 (12.7)	0.83	+11.03	86.5 (11.6)	0.81	+9.83
Speech	99.5 (15.1)	1.76	+21.90	89.3 (11.3)	1.09	+13.20	86.1 (12.0)	0.75	+9.04
Recovery	79.7 (9.68)	0.21	+2.51	73.6 (10.5)	0.37	-5.29	73.4 (8.32)	0.52	-6.26

Note. + = increase, - = decrease. See Figure 4 for a summary of the protocol and time points. Effect size of *d* $(M2 - M1)/SD_{pooled}$ is reported.

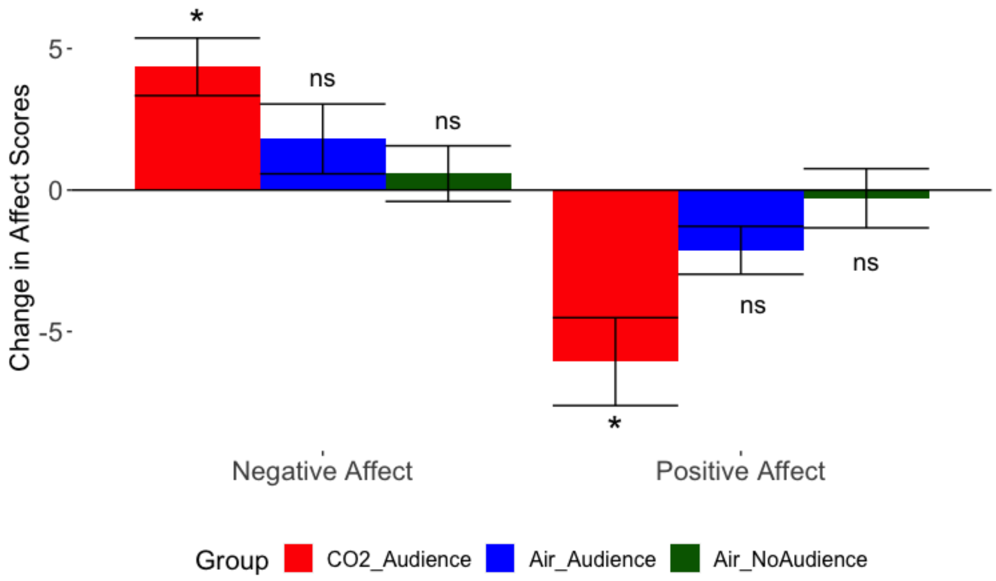
$\eta 2p$ = .066, and on positive affect, $F(2, 90) = 6.18$, $p = .003$, $\eta 2p$ = .121, with medium to large effects. As in Figure 7, our VR paradigm that combined the CO_2 challenge and a virtual audience resulted in significantly higher negative affect, $t(90) = 4.02$, $p <.001$, $d =$ 0.75, and lower positive affect states, $t(90) = 5.11$, $p <.001$, $d = 0.77$. Under regular room air administration, we did not observe any meaningful alterations on negative affect during a virtual performance that took place in front of a large group of virtual avatars, $t(90) =$ 1.67, $p =.099$, $d = 0.33$, or in an empty hall, $t(90) = 0.54$, $p =.593$, $d = 0.14$. Likewise, positive affect states remained stable during the virtual public speaking task for those speaking in the presence, $t(90) = 1.79$, $p =.076$, $d = 0.25$, or absence of a virtual audience $t(90) = 0.245$, $p =.807$, $d = 0.03$. These findings imply that the combined effect of CO_2 and a virtual audience deteriorated the affect during a public speaking task, whilst these observed changes in affect states disappeared if the CO_2 gas and virtual audience elements were decoupled.

Anxiety Sensitivity

We ran a 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 2 (Time: Baseline/Pre, Recovery/Post) linear mixed-effect model on anxiety sensitivity. No significant effects were found for the main effect of Group, $F(2, 90) = 0.77$, $p = .467$, $\eta 2p$ = .017, and Time, $F(1, 90) = 2.95$, $p = .089$, $\eta 2p$ = .032. However, we had a significant

Figure 7

Changes in Negative and Positive Affect Before and After the VR Task Across Groups



Note. Error bars represent the standard error (SE). The Y-axis denotes the change (Recovery/Post –Baseline/Pre) in positive and negative affect. Positive (+) scores on the Y-axis explain positive change in affect. Negative (–) scores explain negative change in affect. ns = not significant. * = *p*< .05.

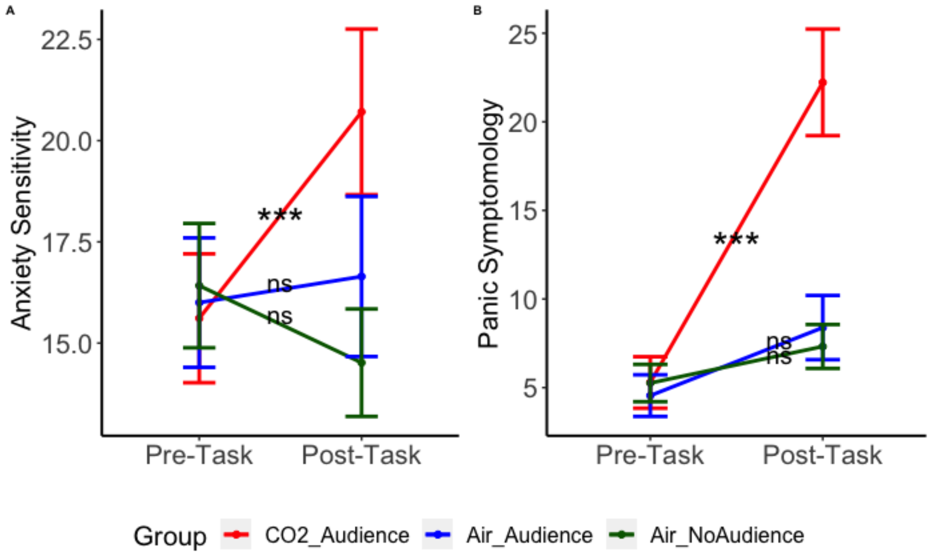
Group*Time interaction, $F(2, 90) = 7.54$, $p < .001$, η2p = .144. As in Figure 8 (left panel), pairwise t-tests suggested that the combination of the CO_2 challenge and performing in the presence of virtual audience (CO_2_Audience) resulted in significant levels of elevated anxiety sensitivity, $t(90) = 3.95$, $p < .001$, $d = 0.50$, whilst no significant pre-post changes were observed for the Air_Audience group, $t(90) = 0.501$, $p = .618$, $d = 0.06$, and for the Air_NoAudience group, $t(90) = 1.47$, $p = .144$, $d = 0.24$. These results highlight the role of combined CO_2 and virtual audience components in enhancing anxiety sensitivity in a public speaking paradigm.

Panic Symptomology

We ran a 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 2 (Time: Baseline/Pre, Recovery/Post) linear mixed-effect model on panic symptom index. Panic symptomology altered as a factor of Group, $F(2, 90) = 8.69$, $p < .001$, η2p = .162, and Time, $F(1, 90) = 43.98$, $p < .001$, η2p = .328. Further, we had a significant Group*Time interaction, $F(2, 90) = 16.69$, $p < .001$, η2p = .271. As evident in Figure 8 (right panel), having performed to a virtual audience under CO_2 administration significantly increased the panic symptomology, (cf. CO_2_Audience, $t(90) = 8.52$, $p < .001$, $d = 1.29$). The change in the panic-like reports has shown a trend toward significance when under regular air influence and performing to a virtual audience (cf. Air_Audience, $t(90) = 1.93$, $p = .057$,

Figure 8

Changes in Anxiety Sensitivity and Panic Symptomology Before and After the VR Task Across Groups



Note. Error bars represent standard error (SE). ns = not significant. ***= *p*<.001.

d = 0.45), and remained unchanged when performing in an empty virtual hall (cf Air_NoAudience group, $t(90) = 1.04$, $p = .302$, $d = 0.32$). Our data suggest that performing to a virtual audience might not be fully sufficient alone to elevate panic-like concerns, whilst performing to a virtual audience under the effect of CO_2 gas might elicit reactivity on panic symptomology.

Performance Evaluations

We ran a 3 (Group: CO_2_Audience, Air_Audience, Air_NoAudience) x 2 (Rating Type: Subject, Observer) linear mixed-effect model using nine items of the original 17-item SPS[5]. The main effect of Group was significant, $F(2, 90) = 3.30$, $p = .041$, η2p = .068. The main effect of Rating Type was significant, $F(1, 90) = 110.69$, $p < .001$, η2p = .552, showing that, in general, participants rated themselves worse than the observer (M_{diff} = 6.60). Further, we had a significant interaction of Group*Rating Type, $F(2, 90) = 3.83$, $p = .025$, η2p = .078. Upon breaking the Group differences by Rating Type, the observer thought that the resulting performances of the participants' speeches were consistent across three Groups, $F(2, 90) = 0.960$, $p = .387$, whereas the participants' own performance ratings differed significantly based on the Group allocation, $F(2, 90) = 4.96$,

[5] We conducted statistical analysis on all 17 items of participant ratings as a factor of Group using one-way ANOVA. Similar findings for participant ratings were obtained. We, therefore, reported the average of nine items as the outcome measure to capture the interaction effects of Group*Rating Type.

p = .009. As shown in Figure 9, probing the effects revealed that the performance ratings of the CO_2_Audience group were significantly lower than the Groups Air_Audience *t(*90) = 2.82, *p* =.018, *d* = 0.71 and Air_NoAudience *t(*90) = 2.63, *p* =.030, *d* = 0.70, whereas the Groups Air_Audience and Air_NoAudience rated their performance similarly, *t(*90) = 0.187, *p* =.999, *d* = 0.05. This finding suggests that, while participants may appear to perform similarly to an observer, their own interpretation of the performance worsened if they spoke to a virtual audience shortly after the CO_2 challenge. However, if no CO_2 gas was administered, the presence or lack of the socially evaluative stimuli that was conveyed through a virtual audience predicted similar performance ratings from the participants' perspectives.

Anticipatory Processing

Our model was conducted on anticipatory processing levels with Group allocation (CO_2_Audience, Air_Audience, Air_NoAudience) as a factor. The three groups differed in their self-report anticipatory processing levels, *F*(2, 90) = 3.51, *p* = .034, η2p = .072. Looking at Figure 10, pairwise t-tests revealed that under regular room air administration, the presence (versus absence) of a virtual audience resulted in similar levels of anticipatory processing (cf. Air_Audience and Air_NoAudience), *t(*90) = 0.381, *p* =.999, *d* = 0.10. Further, preparing and performing the talk to a virtual audience either under the influence of the CO_2 gas or regular room air resulted in similar levels of anticipatory processing (cf. CO_2_Audience and Air_Audience), *t(*90) = 2.08, *p* =.121, *d* = 0.49. The combined elements of the CO_2 gas administration with a subsequent performance to a virtual audience, however, led to significantly worsened levels of anticipatory processing as opposed to the absence of both of these elements (cf. CO_2_Audience and Air_NoAudience), *t(*90) = 2.46, *p* =.047, *d* = 0.66. This finding might imply that in order for anticipatory processing levels to be elevated meaningfully, both the CO_2 gas and a virtual audience that accounts for social evaluation might be needed.

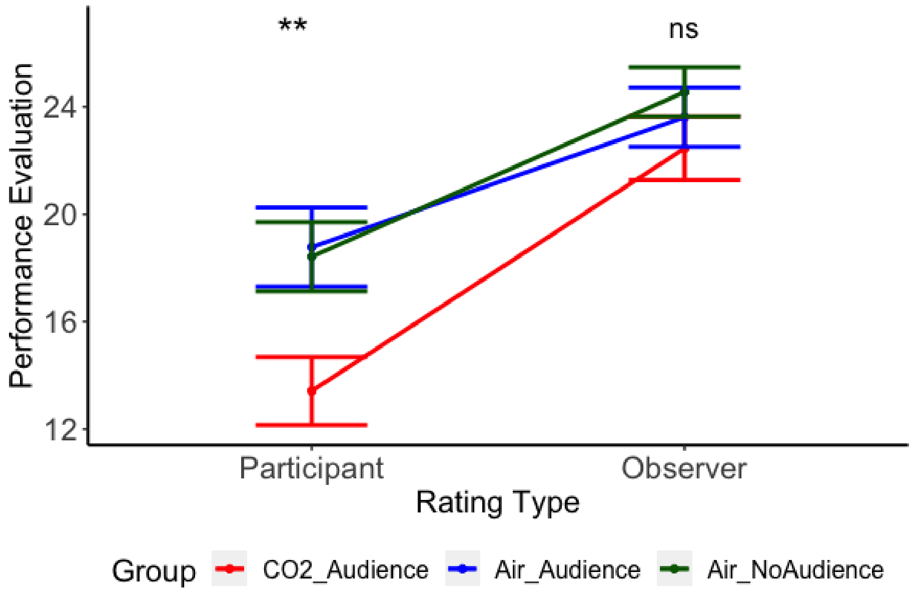
Presence in Virtual Environments

Our model was tested on the presence experienced during the VR task with Group allocation (CO_2_Audience, Air_Audience, Air_NoAudience) as a factor. The three groups differed in their presence levels in virtual environments, *F*(2, 90) = 3.57, *p* = .032, η2p = .074.[6] As shown in Figure 11, pairwise t-tests indicated that, under regular air inhalation, presence levels remained equal whether the talk was prepared and delivered in the presence or absence of a virtual audience (cf. Air_Audience and Air_NoAudience), *t(*90) = 1.57, *p* =.358, *d* = 0.38. When comparing the Groups in which the virtual audience was

[6] We excluded items that were related to sound and haptic from the Presence Questionnaire (PQ).

Figure 9

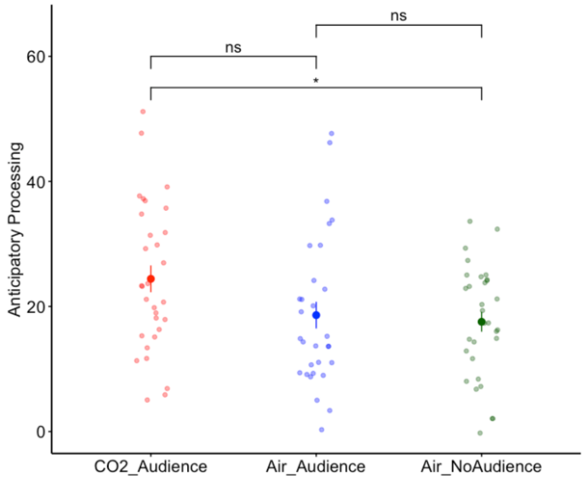
Performance Evaluations from the Participant and the Observer Perspectives Across Groups



Note. Error bars represent standard error (SE). Higher scores account for better performance evaluations. Only nine items of the original 17 item scores are included in the SPS composite values. ns = not significant. ** = *p*<. 01.

Figure 10

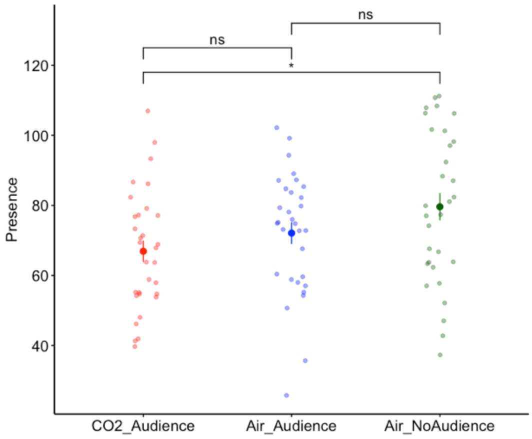
Anticipatory Processing Levels Measured After the VR Task Across Groups



Note. The error bars represent standard error (SE). Higher values on the Y-axis represent more severe anticipatory processing. ns = not significant. * = *p*< .05.

Figure 11

Presence Levels Measured After the VR Task Across Groups



Note. The error bars represent standard error (SE). Higher values on the Y-axis indicate greater experienced presence. ns = not significant. * = $p < .05$.

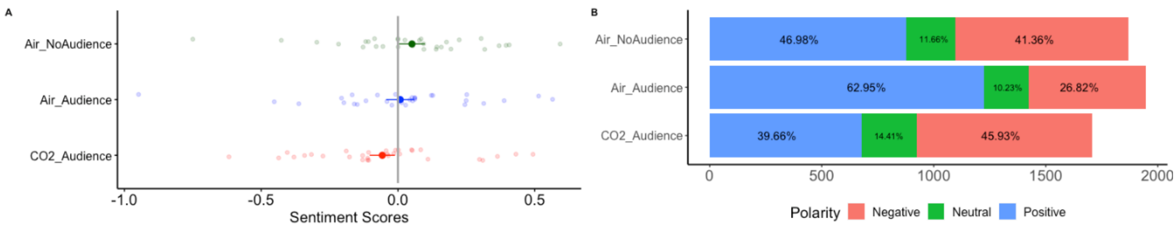
present, the addition of the CO_2 intake did not alter the levels of presence (cf. CO_2_Audience and Air_Audience), $t(90) = 1.08$, $p = .840$, $d = 0.32$. However, preparing and delivering a talk to a virtual audience combined with CO_2 administration resulted in lessened self-reports on presence levels as opposed to preparing and delivering a talk in an empty virtual lecture hall under regular room air administration (cf. CO_2_Audience and Air_NoAudience), $t(90) = 2.66$, $p = .028$, $d = 0.65$. Our data may suggest that the presence experienced in our virtual paradigm may be reduced when presenting to a virtual audience while under the influence of CO_2 gas. However, if these components were exposed separately, the resultant presence feelings in VR might appear relatively equivalent.

Sentiment Analysis

We ran our model in which composite sentiment scores were factored into the Group variable. The three Groups did not differ in their sentiment values, $F(2, 90) = 1.27$, $p = .286$, η2p = .027. Although statistically negligible, as in Figure 12 (panel A), participants' experiences of their public speaking task while exposed to the virtual audience and the CO_2 gas had a slightly negative impact on the semantic scores (M =-0.057, SD = 0.26) when compared to those who performed under regular air administration either when confronted with a virtual audience (M = 0.008, SD = 0.28) or with no audience (M = 0.051, SD = 0.26). Because the sentences were frequently classified as being near to 'neutral' (value 0) in valence in our data, we quantified the 'neutral' semantics between the values of ± 0.001 to examine the positive and negative valanced count data. As demonstrated in Figure 12 (panel B), performing to a virtual audience under the CO_2 gas influence resulted in more frequent negatively valanced narratives (45.93%) than neutral and positively valanced ones. Under regular air

Figure 12

Semantic Valence and the Polarity of the Semantics on the Count Data Across Groups



Note. For Panel A, error bars represent standard error (SE). The vertical dark grey line corresponds to sentiment score zero. For panel B, the neutral sentiment scores were quantitively categorised between ± 0.001.

administration, negative valance was marginally less pronounced for those presented in an empty virtual room (41.36%) and was considerably low when performed in front of a virtual audience (26.82%). To summarise, our anxiogenic paradigm which combines the CO_2 gas and virtual audience may elicit negative sentiments about the virtual public speaking experience, although the bulk of the sentiments in valence were not particularly profound, with values near to zero in valence.

Discussion

Brief Summary

In this study, we investigated the potential of augmenting the 7.5% CO_2 challenge with a subsequent virtual public speaking task to elicit the cognitive and physiological markers of SAD in healthy volunteers. The present study is the first study to demonstrate that the 7.5% CO_2 challenge within a virtual public speaking paradigm exacerbates subjective and objective anxious arousal and might have some specificity to the cognitive mechanisms of SAD.

The findings of our study showed that healthy volunteers who breathed air enriched with 7.5% CO_2 for only five minutes reported significantly higher levels of anxious arousal compared to those who breathed regular room air (+50% increase during the first five minutes of inhaling the gas mixture relative to regular air). Additionally, a 10-minute inhalation of CO_2 before any virtual stimuli were introduced resulted in significantly elevated heart rate levels (+6%) compared to regular room air. These findings are consistent with previous research that reported a peak effect of almost 90% in subjective arousal over baseline and 7-10% increases in objective arousal during a complete 20-minute 7.5% CO_2 challenge (Attwood et al., 2017; Bailey et al., 2006; Bailey et al., 2005; Cooper et al., 2013; Garner et al., 2011). Further, the findings confirm the validity of our manipulation that people who breathed CO_2 experienced heightened subjective and objective arousal after a 10-minute period.

Our virtual public speaking paradigm when combined with the CO_2 administration resulted in heightened negative affect and decreased positive affect. These findings are consistent with previous studies that have used 7.5% CO_2 challenges and compared affect levels of healthy volunteers when inhaling the CO_2 gas mixture or regular room air (Attwood et al., 2015; Attwood et al., 2021; Easey et al., 2018). However, we found that participants who performed under regular room air to a virtual audience did not experience meaningful alterations in their affective processes. This differs from previous studies using the TSST which have reported increased negative affect and decreased positive affect in in-person socially evaluative settings (Vors et al., 2018; Yim et al., 2010). It is possible that merely being exposed to a virtual audience alone may not be sufficient to activate emotional processes, and that the combination with CO_2 administration may be needed for such an effect. However, it is important to consider that our measurements of affect were taken before and after the experimental task, rather than during its peak (i.e., before giving the speech). This could explain why the air-inhaled groups' affect may have returned to their baseline levels, resulting in null findings. In addition, one could argue that the significant findings on affect for the CO_2-inhaled group are redundant given our timing of data measurement. However, these findings may suggest that the combination of a virtual audience and CO_2 administration leads to a longer duration of activated affective processes compared to the virtual audience alone.

This combination of our virtual public speaking paradigm with CO_2 administration increased reporting of panic symptomology and anxiety sensitivity. Panic attacks are often observed in individuals with SAD (Stein & Stein, 2008), and anxiety sensitivity has been identified as a predictor of social anxiety (Brooke & Intrieri, 2021; Moore et al., 2009). Thus, our paradigm may closely resemble social anxiety in these variables, providing confidence in its potential adaptation for social anxiety research. In the following sections, we will further analyse our results in relation to existing anxiogenic paradigms and their potential relevance for the cognitive mechanisms of SAD.

Anxiogenic Effect of Virtual Audience and CO_2 Combination

As hypothesised, our findings indicate that exposing participants to a brief speech task in the presence of a virtual audience under a CO_2 administration (as opposed to breathing regular air) led to significantly higher levels of both subjective and objective anxiety that were acute in nature. According to cognitive models, one of the key processing biases in SAD during social encounters is a switch in attention to internal cues that might be distorted at cognitive (e.g., I am blushed) or behavioural (e.g., I am shaking) levels (Rapee & Heimberg, 1997). It is possible that, in our investigation, internal attentional cues might have been heightened via the CO_2 gas administration. This, in turn, might have fed into an adversely biased external scanning of the environment seeking negative approval, contributing to heightened responses in both subjective and objective anxious arousal. Indeed, Rapee and Abbott (2007) provided evidence that socially anxious people tend to experience heightened anxiety during a socially evaluative speech task through inappropriate attentional focus (e.g., focusing on heartbeat). As our study was a proof-of-concept, we did not incorporate a measure of self-focused attention to clarify this relationship in our data. Therefore, this question may require further exploration, particularly since our results indicated that the combination of CO_2 and a socially evaluative task in VR led to an increase in situational anxiety. Our findings are consistent with studies testing patients diagnosed with clinical SAD in virtual social scenarios that reported heightened subjective anxious arousal (Felnhofer et al., 2014), and a peak 17% increase in heart rate levels (Owens & Beidel, 2015). Our study involving healthy volunteers presented under the combination of a CO_2 challenge and virtual audience aligns with this previous research. Our findings showed that the participants experienced nearly 80% peak in subjective anxiety, and slightly over 20% peak in heart rate levels (Table 5 and Table 6).

Anxiogenic Effect of Virtual Audience Under Air Inhalations

Having performed to a socially evaluative threat conveyed through a virtual audience (versus a control condition with no audience) while breathing regular air in a virtual public speaking task did not result in an increase in either subjective or objective anxious arousal. This lack of effect, as opposed to previous work which reported significant effects (Jönsson et al., 2010; Kothgassner et al., 2019; Kothgassner, Hlavacs, et al., 2016), may be due to the different ways in which the control condition was assigned in previous research. For instance, when testing the effects of a TSST paradigm on healthy people, Kothgassner et al. (2021) used a control condition with no socially evaluative threat similar to the current research design, but their design allowed participants to talk about any topic they chose. We imposed all groups of participants to talk about a non-emotional topic (i.e., Artificial Intelligence). Although we failed to record the between-subjects differences on familiarity with the topic, imposing participants to talk about a pre-determined topic could still lead to a sense of uncontrollability that was associated with increased anxious responses in social situations (Dickerson & Kemeny, 2004). In addition, during the anticipation and preparation phase of our study, participants were able to see the virtual audience, even though the audience appeared to be uninterested and not paying attention to the participant (i.e., not looking at them and talking to each other). However, this exposure to the virtual audience may have resulted in a habituation mechanism that could have reduced the peak anxious effects when the participants were delivering their speeches, especially when comparing the effects of the virtual audience's absence/presence under normal air inhalation, which is related to social evaluative threat. The habituation effects of these speech paradigms have not been explored within the same day. However, it has been noted that replicating anxiogenic responses within speech paradigms might require longer time intervals, ideally more than one day (Kothgassner et al., 2021).

How Does CO_2 and Virtual Audience Combination Modulate Psychological Mechanisms in SAD?

Performance Evaluations

Our data indicated that the participants rated their performance worse when exposed to the combination of CO_2 and a virtual audience compared to any other group within our design, while observer ratings of performance were comparable across all groups. Consistent findings were obtained in previous research, demonstrating that people with SAD do not actually perform poorly (Rapee & Lim, 1992; Strahan & Conger, 1998), but they do tend to underestimate their performance in speech tasks compared to how external observers perceive their performance (Brozovich & Heimberg, 2011; Cheng et al., 2017; Gallego et al., 2022; Perini et al., 2006; Spurr & Stopa, 2003). The current study, which was conducted on healthy individuals, showed this underestimation pattern where the use of a CO_2 gas mixture and a virtual audience led to more negative self-evaluations of performance than observer evaluations.

Anticipatory Processing

Our findings suggested that the participants who were exposed to a combination of CO_2 gas and a virtual audience showed meaningful increases in anticipatory processing, whilst the sole effect of gas versus normal room air (when performing to a virtual audience), or the presence of a virtual audience versus absence of a virtual audience (under air administration), resulted in comparable negative anticipation. In other words, we found the existence of meaningful levels of retrospective anticipatory processing only when the performance took place facing virtual avatars and under the influence of CO_2 gas. Anticipatory processing is commonly experienced by people with SAD before a feared social event (Laposa & Rector, 2016; Vassilopoulos, 2004; Vassilopoulos et al., 2017), but not by those without social anxiety (Vassilopoulos, 2005). Mills et al. (2014) indicated that people with SAD who engage in anticipatory processing tend to have a stronger focus on self-referential heart rate feedback compared to those without social anxiety. This indicates that anticipatory processing might cause a shift of attention inward, towards the self. In our design, it is possible that the retrospective assessment of anticipatory processing at the end of our experimental protocol was influenced by participants' experience with the CO_2 gas, which could have served as internal feedback for them to focus on their heightened heart rate levels. This, in turn, could have intensified their anticipatory ruminations about their speech preparation phase. It is informative to replicate our findings by measuring participants' levels of anticipatory processing before the CO_2 administration and virtual public speaking task on a separate lab day. Nevertheless, these are promising findings as the combination of CO_2 gas and a virtual audience may be able to replicate some of the mechanisms seen in SAD in healthy individuals, providing a useful tool for studying the underlying processes involved in SAD.

Other Exploratory Constructs

Presence

Presence is defined as the degree to which an individual feels linked to or engaged with virtual stimuli or setting in virtual environments. From a methodological point, presence might come as an important factor to consider in VR research, however, the literature is not consistent. For instance, presence was linked to the success of anxious activation during acute anxiety evoking paradigms (Diemer & Zwanzger, 2019; Price & Anderson, 2007). In addition, previous work reported that the presence concept is associated with heightened situational anxiety (Bouchard et al., 2008), although some others failed to find a complete association of presence and experienced anxious arousal during anxiogenic paradigms (Felnhofer et al., 2014; Morina et al., 2014). Our findings suggested that people who performed in front of a virtual audience under the influence of CO_2 gas reported the lowest levels of presence (versus regular room air and empty virtual room). One speculation for our findings might be that the physiological symptoms (i.e., heart rate) induced by CO_2 may not fully align with the cognitive processing of these symptoms. In other words, since CO_2 operates by altering the body's acidosis level, it may be challenging for participants to reconcile the increased physiological symptoms with their corresponding cognitive threat appraisals. This could have led participants to focus more on internal, cardiovascular self-cues (i.e., interoceptive awareness) than on the virtual audience, which could have affected their perception of the presence of the virtual environment. Although social anxiety is modulated by body-state information (i.e., false pulse rate feedback leading to increases in anxiety) (Wells & Papageorgiou, 2001), the added anxiogenic CO_2 effect is not natural. Therefore, it might have disrupted the perceptual cues that could be allocated for scanning the virtual social environment. Additionally, Felnhofer et al. (2014) failed to find a mediating effect of presence when examining anxious arousal for people with low and high anxiety during a virtual socially evaluative set-up. Their interpretation was that presence only acts as a prerequisite to activate an emotion and does not affect its intensity, which could be the case considering our findings. Furthermore, it is important to note that the measurement of presence and how it is defined in the literature can be problematic (Slater et al., 1999). Therefore, it may be informative to consider alternative measures of presence (Schubert et al., 2001) in future studies.

Sentiments

Fully exploratory, we found that a performance under the combination of CO_2 and virtual audience produced negatively valanced sentiments, although most sentiments were close to neutral in valence range. There is limited research investigating how individuals with SAD process language during socially evaluative situations. Only one study, by Hofmann et al. (2012), examined participants' use of negative and positive emotional words and self and other referential statements (i.e., 'I' versus 'we') during a public speaking task. The authors reported that people with SAD used positive emotional words more often relative to a control group, suggesting that people with SAD might use language in a way to reduce threat appraisals. They did not find any group differences for negative sentiments. For our analysis, we analysed the data from the written qualitative descriptions of the experimental protocol (and not the actual speeches of participants). The findings revealed that the combination of CO_2 and virtual audience led to more negative sentiments. Investigating how language during a speech or conversation scenario is processed under standard anxiogenic laboratory protocols could be a valuable avenue for future research in studying SAD. In addition, free speech has been offered as a therapeutic tool for social anxiety (Qu et al., 2013). This highlights the importance of conducting language analyses to better understand the effects of speech paradigms on people with social anxiety.

Limitations and Future Research

There are number of limitations to this study. We recognise that this study did not have a strictly controlled orthogonal design wherein both manipulation techniques (i.e., CO_2-air inhalation versus audience-no audience in virtual environments) were compared independently to each other as well as to a true baseline (e.g., with no performance component). Such a comparison would have depicted a more complete image in weighing the contribution of each manipulation in generating anxious states. Although we were still able to observe the effects of a virtual audience and CO_2/air inhalation in a particular order, one might argue whether the anxiogenic effects we observed (CO_2_Audience versus Air_Audience) resulted from a combined effect or solely from CO_2 exposure, given that there was no anxiogenic effect of virtual audience under normal room air conditions (cf. Air_Audience, Air_NoAudience). However, previous research has demonstrated that CO_2 can induce both subjective and objective anxious arousal in the absence of social evaluative threat (Bailey et al., 2006; Bailey et al., 2005; Bailey et al., 2011). This study was designed to investigate whether the CO_2 mixture amplifies social evaluative threat, which indeed it did. Employing an orthogonal 2x2 design would have overly stretched our project in terms of data collection and use of resources and have made it more challenging to detect the effects we were interested in. Second, we examined the state anxious arousal within the model based on the peak effects on broad situational anxiety measures ($GAD\text{-}7_{Modified}$, SUDS). This information might have limited the clinical expression of SAD. Instead, it would have been more informative to include situational measures that may represent SAD more accurately within the experimental protocol (Hayes et al., 2008). In addition, participants were able to see the virtual audience during the preparation/anticipation period of the experimental protocol, even though the audience appeared to be uninterested and not paying attention to the participant (i.e., not looking at them and talking to each other). While not necessarily a limitation, this could have caused habituation effects influencing the detected significance and effect size magnitude (as mentioned earlier), and should be considered when comparing this study to previous work.

Given that the anxiogenic effects of this paradigm are promising, future work might benefit by exploring the self-focused attention mechanism within this paradigm by administering a subjective self-report or recording gaze pattern in VR to quantify self-focused attention. In addition, different techniques of anxiogenic challenges might activate distinct patterns of brain functioning (e.g., hypothalamic-pituitary adrenal versus sympathetic nervous system) (Du Plooy et al., 2014), and neuroimaging studies might be informative in understanding this combination for SAD.

Conclusion

This study contributes to the expanding research on experimental models of anxiety and provides new findings on the potential effectiveness of the CO_2 challenge in increasing situational anxiety during a public speaking scenario. Additionally, our exploration of this paradigm offers a promising approach to investigating the cognitive mechanisms of SAD within standardised laboratory settings. These findings may encourage adaptations of evidence-based human anxiety models in laboratory settings for the study of SAD, eventually informing the development of more effective treatment strategies for individuals with SAD.

Chapter 3 – Evaluating Photorealistic 360° VR Environments for Social Anxiety Research

Abstract

Public speaking tasks are frequently employed as anxiogenic laboratory paradigms to elicit anxiety and social evaluative stress. Research suggests that socially anxious people experience higher levels of anxiety when facing socially evaluative situations, and that the anxious states encountered during such scenarios can be a significant predictor of social anxiety. We developed a photorealistic virtual reality (VR) paradigm and tested its potential as an anxiogenic laboratory protocol in a nonclinical sample. We examined predictors of anxiety in this model, including self-reported trait generalised and social anxiety, predictors of state anxiety, performance evaluations, post-event processing, and sense of presence. Finally, we examined how the photorealistic virtual public speaking paradigm predicted anxious arousal in a subsequent *in-person* social task. Although the effects on state anxious arousal were comparable when performing in the presence of a virtual audience versus in an empty room, our findings provided some evidence of the relevance of situational and trait *social anxiety* to our virtual paradigm. We also observed anxious reactivity during the subsequent in-person socially evaluative task. Our study provides a proof-of-concept that photorealistic 360-degree VR has some utility in social anxiety laboratory research.

Keywords: virtual reality, social anxiety, public speaking

Introduction

Psychological paradigms that involve social evaluation (e.g., evaluative members of a jury/audience, uncontrollability) have been shown to elicit the psychological and behavioural features of social anxiety (Dickerson & Kemeny, 2004; Frisch et al., 2015). It is argued that socially evaluative threat occurs in social situations where a valued aspect of personal characteristics (e.g., intelligence) is visible to observers and can be negatively judged (e.g., by an audience or a panel of judges) (Dickerson & Kemeny, 2004; Wong et al., 2020). In their meta-analysis, Dickerson and Kemeny (2004) found that tasks with elements of social evaluation were associated with higher cortisol responses (moderate effect, d=0.67) than tasks without (small effect, d=0.21). In addition to cortisol response, subjective anxiety and negative cognitive biases were observed within socially evaluative paradigms (Dickerson, 2008; Dickerson et al., 2008).

Public speaking tasks, in this regard, are often utilised in laboratories as anxiogenic psychological paradigms to model socially evaluative threat (see Osório et al. (2008) for a review). The most widely studied psychological experimental social stress paradigm is the Trier Social Stress Test (TSST) (Kirschbaum et al., 1993). In a standard TSST protocol, participants would be asked to make an impromptu oral presentation (five minutes) after a brief task introduction and a preparation period (10 minutes), and subsequently perform a surprising mental arithmetic task (five minutes) in front of a panel of three judges. During the task, the judges would refrain from providing feedback or encouragement, whilst the participants are made to believe that their performance would be recorded (see Allen et al. (2017) for a detailed protocol). The TSST protocol can reliably evoke subjective anxious arousal (Allen et al., 2014), negative mood (Yim et al., 2010), and increase heart rate (with a peak mean increase of 15 to 25 beats per minute over baseline) (Kudielka et al., 2007). In addition, a recent meta-analysis (n=186) yielded large effects of TSST on cortisol reactivity (Cohen's d =.93) in healthy volunteers (Goodman et al., 2017). Although these findings suggest public speaking tasks can elicit subjective and physiological responses, Buchanan et al. (2012) provided evidence that a panel of judges exhibited anxiogenic responses proportionate to their matched speaker (i.e., emotion contagion) during a TSST. To enable appropriate experimental control, panel feedback should be consistent across participants. Furthermore, these paradigms employing real persons are associated with relatively high costs (e.g., a dummy audience/actors hire) and potential logistical barriers (e.g., booking a room).

Virtual Reality (VR) is a novel technological tool that can simulate real-life social scenarios while preserving experimental rigour and control (Kothgassner & Felnhofer, 2020; Slater & Sanchez-Vives, 2016). Typically, VR technology offers immersive computer-generated worlds, presented via a head mounted display, that fully replace sensory experiences with digitally created ones, where users view a complete stereoscopic visual field (Blascovich et al., 2002; Rizzo & Koenig, 2017). Developing anxiogenic virtual paradigms may have various advantages, including the ability to control confounding factors (e.g., confederate behaviour), manipulate environment variables as required, and standardise social interaction scenarios (Gaggioli, 2001). Various research groups have developed and validated the anxiogenic ability of VR based psychological laboratory paradigms on subjective (e.g., self-report questionnaires) and objective reactivity (e.g., heart rate, cortisol levels, or electrodermal activity), in which socially evaluative threat is conveyed through virtual avatars within TSST protocols (Fallon et al., 2016; Jönsson et al., 2010; Kothgassner, Hlavacs, et al., 2016; Montero-López et al., 2016; Shiban et al., 2016; Wallergård et al., 2011; Zimmer, Buttlar, et al., 2019) and in public speaking scenarios (Kothgassner, Felnhofer, et al., 2016). Further, recent meta-analyses have reported heightened physiological responses to anxiogenic paradigms conducted in VR (baseline-to-peak d = 0.68 for heart rate levels) (van Dammen et al., 2022), although the anxious arousal was experienced to a lesser extent in VR than in real-life anxiogenic paradigms (Helminen et al., 2019).

Contemporary theories suggest that in social anxiety disorder (SAD), socially evaluative stimuli trigger fears of negative evaluation, that in turn is linked to heightened states of anxious arousal (Rapee & Heimberg, 1997; Wong et al., 2020) that impairs social performance (Voncken & Bögels, 2008) and increases negative post-event processing (Wong & Rapee, 2016). Evidence exists that increased states of anxious arousal in a socially evaluative scenario has been observed in socially anxious populations (Huneke et al., 2022; Roelofs et al., 2009), with the objective arousal reactivity being larger in people with social anxiety compared to other anxiety-related disorders and healthy controls (Roelofs et al., 2009). In addition, subjective anxious states during a socially evaluative scenario are reported to be a significant predictor in the maintenance of social anxiety (Nelemans et al., 2017). Therefore, it can be argued that experimental models that introduce socially evaluative stimuli, such as a public speaking scenario, may have some validity with respect to the clinical expression of social anxiety. This, in turn, may provide an opportunity to further explore the disorder within a controlled laboratory setting.

Traditional exposure therapy entails repeatedly and systematically exposing the individual to feared stimuli in a safe setting until the fear response has been inhibited (or habituated) and replaced by new associations (Abramowitz, 2013; Abramowitz et al., 2019) (Foa & Kozak, 1986, 2019). Further, to obtain optimised treatment outcomes, habituation response should occur during and between exposures (Craske et al., 2008; Foa & Kozak, 2019). Although between-session habituation on anxious arousal has been observed in real-life (Finn et al., 2009) and virtual public speaking scenarios for clinical samples of SAD (Morina et al., 2015) and non-clinical populations (Jönsson et al., 2010; Takac et al., 2019), investigations on whether a socially evaluative exposure experienced in VR would habituate responses during a subsequent socially evaluative *real-life* task are lacking. Meta-analyses have reported the efficacy of exposure therapy within VR for clinical SAD populations (Opriş et al., 2012), and the treatment outcomes of VR exposure were comparable to the real-life or imaginary exposure (Chesham et al., 2018). Furthermore, a broad array of socially evaluative stimuli including party scenarios (Parrish et al., 2016), shopping mall scenarios (Rinck et al., 2010), a train scenario (Dechant et al., 2017), and, most notably, public speaking scenarios (Felnhofer et al., 2018; Kim et al., 2018; Owens & Beidel, 2015) have been introduced into virtual settings for SAD further to investigate the disorder. Hence, testing the transferable anxiogenic effects of a socially evaluative scenario within VR to a subsequent *real-life* stressful task on a non-clinical sample would provide reference data on the initial evidence of the role of VR exposure in habituation theory (Foa & Kozak, 1986), and would further inform the credibility of VR modelling into real-life SAD symptomology for therapeutic purposes.

Using VR in research and clinical practice is becoming increasingly viable due to declining hardware costs and the availability of affordable devices (Bun et al., 2017). Yet, creating computer generated graphics in VR requires a high degree of programming expertise and effort, or considerable financial means to outsource these efforts (Bohil et al., 2011). Immersive 360° video technology might have the ability to address this constraint. In contrast to computer-generated scenarios, 360° videos are often recorded using an omni-directional camera (or several cameras) and can be directly transferred into VR via easy-to-navigate and widely available software packages for an immersive and photorealistic virtual experience. Aside from the convenience with which anxiogenic protocols may be generated, 360° videos significantly increase users' feeling of presence, yielding positive results in treatment modalities within healthcare settings due to the novelty of real-life scenario involvement (Ionescu et al., 2021). This emerging technology has recently been integrated into socially evaluative scenarios where audience reactions (Barreda-Ángeles et al., 2020) or audience size (Stupar-Rutenfrans et al., 2017) have been manipulated, or a protocol resembling TSST has been adapted (Rubin et al., 2020; Rubin et al., 2022; Schebella et al., 2019). The data supported the ability of 360° technology to induce anxious arousal, although methodological differences arose. That is, either the use of equipment differed (i.e., mobile phones) (Stupar-Rutenfrans et al., 2017), or no control scenario was utilised (Barreda-Ángeles et al., 2020; Rubin et al., 2022). One recent work exploring 360° VR exposure for people high in public speaking anxiety with gradual exposure that was delivered in four sessions reported greater reductions in subjective social anxiety symptoms, as opposed to performing in an empty virtual hall or to a control group, by the end of the fourth session (Reeves et al., 2021). However, the 360° technology has never been tested on a non-clinical sample within a single protocol where multiple outcome measures are taken to investigate anxiety reactivity throughout a single exposure. In addition, the relevance of a 360° virtual public speaking paradigm to SAD is yet to be investigated empirically.

An essential next step in implementing 360° technology could be the development of novel standardised protocols to improve the quality of research and evidence-based interventions. The first objective of the present study was to assess whether a photorealistic VR environment with a pre-recorded real audience would induce subjective (self-reported) and objective (heart rate) anxious arousal over time for a non-clinical sample during a virtual public speaking task as opposed to performing in an empty virtual hall. We hypothesised to observe linear increases over baseline periods in anxious arousal until recovery, based on the previous studies on stress induction methods on a non-clinical population employing stress induction protocols in VR (Kothgassner, Felnhofer, et al., 2016). Importantly, we expected the magnitude of anxious arousal to be greater among the group who performed in the presence of an audience in VR, especially just before delivering the talk.

The second objective was to investigate whether photorealistic VR exposure would habituate anxious arousal during a subsequent socially evaluative in-person task. A short real-life mental arithmetic task was designed in which the difficulty of calculation questions varied. Tasks utilising the mechanisms of a motivated performance that demands immediate overt responses from the participant in the presence of a socially evaluative threat (i.e., a panel of judges) has been shown to be a reliable combination in eliciting anxious response (d = 0.35) (Dickerson & Kemeny, 2004), including in-person mathematical tasks (Kotlyar et al., 2008; Zubair & Yoon, 2019). Based on the evidence on the habituation literature (Jönsson et al., 2010; Takac et al., 2019), we hypothesised that while a subsequent face-to-face socially evaluative task would raise overall anxiety levels, the increment in the objective and subjective anxious response would be less prominent for those who performed in a photorealistic VR scenario when populated with an audience, relative to performing in empty virtual lecture halls.

We also examined the extent to which self-reported measures of trait social anxiety and generalised anxiety would better predict elevated in-situ self-reported anxiety in our photorealistic paradigm (versus No Audience control group). We also predicted the effects at between-group changes in mood, anxiety sensitivity, and panic symptoms (pre and post VR speech performance). Finally, we examined the between-group differences on the cognitive mechanisms of social anxiety (i.e., post-event processing, performance evaluations) as well as presence felt in virtual environments, measured in the aftermath of the VR performance.

Method

The data were collected between March 2022 and June 2022 (inclusive). Participants provided online informed consent prior to the experiment. The study was approved by the University of Southampton Research Ethics Committee (reference: 67176). Participants were offered monetary compensation (£17.50) or research credit allocation (for psychology students). We preregistered this study (28/05/2022): https://doi.org/10.17605/OSF.IO/NXT9Q

Participants

Participants were recruited using university-based channels (i.e., Efolio, https://www.efolio.soton.ac.uk/) or through social media adverts and physical leaflets distributed on campus. We included participants if they were aged between 18 and 55, were fluent in English, and did not wear glasses for vision correction (due to the VR fitting). Prior to testing, the participants were randomly allocated to one of the two experimental conditions using a computerised research randomiser (https://www.randomizer.org/): a group who performed in the presence of a pre-recorded audience in VR (Audience); and a group who performed in an empty virtual lecture hall (No Audience). The sample size comprised 64 participants (35 females, aged between 18 and 46 years (M_{age} = 25.31, SD_{age} = 7.32).

Power and Sensitivity Analyses

We used the G*Power software version 3.1.to conduct a power analysis (Faul et al., 2007). Corresponding to our main hypothesis, we specified an *a priori* 2 (Group) x 5 (Time) within-between interaction with a medium effect size (Cohen's f = 0.25) at 80% power and 5% type I error probability. Considering the observed double dissociation effect in G*Power (i.e., a positive effect in one group versus a similar negative effect in the second group), we halved the effect size (Cohen's f = 0.125). The recommended sample size was 78. We were able to recruit 64 participants.

Due to study potentially being underpowered, we conducted a sensitivity analysis to determine the smallest effect that is reliably detectable using G*Power software version 3.1 (Faul et al., 2007). The interaction effects (for primary measures) with 64 participants would be sensitive to the effects of η^2 = 0.125 and above with 80% power and 5% type I error probability. This consideration will inform our interpretation of the main findings (see Results section).

Materials

Scene Development and Technical Equipment

We pre-recorded a lecture theatre at the University of Southampton's Psychology department twice with an Insta360 Pro 2 (https://www.insta360.com), an 8K 360° video camera: (i) when the lecture room was non-populated; and (ii) when it was populated with a real audience. As shown in Figure 13, 21 young adults (nine females) formed the audience, who kept neutral facial expressions throughout the recording. Prior to the

Figure 13

Example Scenes from the Virtual Environment

Note. Panels (A) and (B) illustrate the virtual environment with an audience during the anticipation phase whilst the audience took their seats and were non-attentive for three minutes. (C) illustrates the time when the participant delivered their rehearsed speech for three minutes to an attentive audience. (D) illustrates the empty virtual environment.

filming, they provided their consent to the recordings and the potential public release of the footage.

Recorded raw videos have been stitched using Insta360 STITCHER (content type: stereo, left eye on top, stitching mode: new optical flow, Zenith optimisation on). The footage was then encoded using the Handbrake application (https://handbrake.fr/) before being transferred into the Unity software. The source code was written in C# using Visual Studio version 15.9.38. The videos were trimmed to time periods six minutes long, which corresponded to a preparation phase of three minutes and a speech phase of three minutes.

The VR equipment used was the Oculus Rift consumer version headset (Facebook Inc.) with integrated audio system, offering a 110-degree of field view with 640×800 resolution per eye, which was running on a Dell Desktop computer with an Intel i7 processor (Windows 10 operating system). Participant response input was recorded using the Oculus Rift Bluetooth touch controller.

Measures

Baseline Measures

To characterise our sample, we measured the levels of trait anxiety via the Generalised Anxiety Disorder Assesment (GAD-7) (Spitzer et al., 2006), trait social anxiety via the Social Phobia Inventory (SPIN) (Connor et al., 2000), trait social anxiety in relation to interacting with others via the Social Interaction Anxiety Scale (SIAS) (Mattick & Clarke, 1998), and trait social anxiety in relation to experienced avoidance and fear during interaction and performance related social events via the Liebowitz Social Anxiety Scale (LSAS) (Liebowitz, 1987). Although LSAS has been developed as a clinically administered measure, the explorations on the self-report version had good psychometric properties (Baker et al., 2002; Fresco et al., 2001; Oakman et al., 2003). We also measured communication apprehension levels (given that participants performed a public speaking task) by administering the Personal Report of Communication Apprehension - public speaking sub scale (PRCA-24) (McCroskey, 2015). Finally, we collected self-reported data for depression severity (Patient Health Questionnaire, PHQ-9) (Kroenke & Spitzer, 2002) and paranoia levels (the Revisited Green Paranoid Thoughts Scale - Persecutory Paranoia Subscale, R-GPTS) (Freeman et al., 2019). Because the face-to-face socially evaluative task included basic mathematical calculations, participants also completed The Abbreviated Math Anxiety Scale (AMAS) (Hopko et al., 2003) to record between-group differences on maths-related anxiety. This scale has nine items (e.g., ‘Being given a pop quiz in math class’) and is measured on a five-point scale (low anxiety = 1, high anxiety = 5).

Primary Outcome Measures

GAD-7$_{Modified}$.

Participants completed GAD-7$_{Modified}$, a modified version of the seven-item GAD-7 (Spitzer et al., 2006), to measure state anxiety severity. Participants rated their level of anxiety in response to the question, ‘How often have you been bothered by the following *right now*?’ on several aspects of anxious arousal (e.g., ‘trouble relaxing’), on a scale ranging from 0 (not at all) to 3 (all the time). As a broad self-report anxiety severity measure, GAD-7 showed sound psychometric properties (α= .89) in the non-clinical population (Löwe et al., 2008). The GAD-7$_{Modified}$ for our sample at the baseline showed good α of .92 (95% CI = .85 - .95, bootstrapped based on 1,000 samples).

Subjective Units of Distress (SUDS)

Participants rated their state anxiety at certain stages of the experiment in response to the question, ‘How anxious do you feel right now?’ on a visual analogue scale (VAS) ranging from 0 (not at all) to 100 (extremely anxious) (Wolpe, 1990). While multiple-item measures are ideal, research has demonstrated that single-item response scales such as VAS can correctly assess situational anxiety (Davey et al., 2007).

Social Anxiety Session Change Index ($SASCI_{Modified}$)

Participants rated their state social anxiety using the Social Anxiety Session Change Index (SASCI) (Hayes et al., 2008). SASCI is a four-item instrument that has been developed to monitor therapy progress for clinicians and is rated on a seven-point Likert-type scale ranging from 1 (much less than at the start of treatment) to 4 (not different from at the start of treatment) to 7 (much more than at the start of treatment). We modified the items (e.g., ‘How concerned are you that others are thinking badly of you?’) as well as the scoring range (0 = not at all, 4 = extremely). Across therapy sessions, SASCI showed good to excellent psychometric properties on a clinical sample (α = .84 - .94) (Hayes et al., 2008). In our sample, the $SASCI_{Modified}$ at baseline showed an α of .82 (95% CI = .72 - .87, bootstrapped based on 1,000 samples). See Appendix C for the modified version.

Heart Rate

We used publicly available wrist worn activity trackers to record physiological data. Continuous heart rate data was collected using Fitbit Charge 2 wrist-worn smart watches (Fitbit Inc., https://www.fitbit.com). Fitbit Charge 2 uses photoplethysmography (PPG) signals as a non-invasive measurement method which is routinely used for health monitoring. Across different devices, PPG signals are often obtained at red, near infra-red or green light. Fitbit Charge 2 uses a green light source and a photodetector at the surface of the skin to measure the volumetric variations of blood circulation (Castaneda et al., 2018). Each participant was connected to two Fitbit Charge 2 smart watches. The smart watches were linked to two generic Fitbit accounts, and the corresponding information (i.e., wrist - left, right) was entered for both watches prior to each testing. Previous research has reported that heart rate accuracy estimations via Fitbit watches are within a reasonable range, with a measurement error of 4% compared to reliable criterion measurements (ActiGraph, Yamax or Polar H7) (Bai et al., 2021).

Exploratory Measures

Positive and Negative Affect Scale (PANAS)

Participants recorded their self-reported negative and positive mood via the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988). PANAS consists of two 10-item subscales that correspond to positive mood (e.g., interested) and negative mood (e.g., distressed) with excellent psychometric properties ($\alpha_{positive\ affect}$ =.89, $\alpha_{negative\ affect}$ =.85 (Crawford & Henry, 2004). It is rated on a five-point scale (1 = very slightly or not at all, 4 = extremely). Participants recorded their mood before and after the VR task with modified instructions (i.e., 'Indicate to what extent you feel this way *right now, that is, at the present moment*').

Anxiety Sensitivity Index (ASI)

ASI (Reiss et al., 1986) includes 16 items (e.g., 'It scares me when my heart beats rapidly') to measure propensity to fear the somatic and cognitive symptoms of anxiety due to the belief that these symptoms could be harmful. Each item is rated on a five-point scale (0 = very little, 4 = very much). ASI has been widely used to measure the anxiety sensitivity construct with good psychometric properties (Peterson et al., 1999; Peterson & Heilbronner, 1987). We modified the instructions to be able to capture the anxiety sensitivity experienced at baseline (i.e., 'Please click on the one phrase that best represents the extent to which you agree with each item below right now') and during the participants' VR performance (i.e., 'Please click on the one phrase that best represents the extent to which you agree with each item below reflecting back on the task you completed in VR').

Panic Symptom Inventory (PSI)

We assessed the somatic and cognitive panic symptoms by administering a 35-item rating sheet (e.g., heart racing), with a five-point scale ranging from 0 (not at all) to 4 (very severe) (Clark & Hemsley, 1982). We instructed the participants to self-report their panic symptoms at that present moment before and after their VR performance.

Speech Performance Scale (SPS)

SPS (Rapee & Lim, 1992) is a 17-item instrument with some reverse coded items (e.g., 'I had a clear voice', 'I was blushing'), and is rated on a scale ranging from 0 (not at all) to 4 (very much). Higher scores account for better performance evaluation. Participants completed this measure twice: the first administration was based on their performance from their point of view (self, how you felt you actually performed), and the second administration was based on others' points of view (observer, how you think others felt when you performed), regarding their performance.

Thoughts Questionnaire (TQ)

The TQ consists of 29 items (three sub scales, 11 negative ruminations, e.g., "I must have looked stupid"; 16 positive ruminations, e.g., "My speech was good"; and two general ruminations, e.g., the situation overall), which are rated on a scale ranging from 0 (never) to 4 (very often). Higher scores indicate more persistent post-event processing (negative, positive, or general). We used the negative rumination subscales for the analysis on post-event processing. The TQ showed excellent psychometric properties across subscales (α = .79 -. 94) (Edwards et al., 2003).

Presence in Virtual Environment

The sense of being in a virtual environment (aka presence (Slater, 2003)) was measured using the Presence Questionnaire (Witmer & Singer, 1998). The questionnaire has 24 items that assess various aspects of the VR experience, including realism, ability to interact, interface quality, examination possibilities, self-evaluation of performance, audio, and haptic experience. We removed two items from the questionnaire that were related to the haptic subscale, as our virtual environment did not incorporate any tactile sensations. One example item of the realism subscale is 'How much did your experiences in the virtual environment seem consistent with your real-world experiences?'. Participants were asked to rate their response on a VAS ranging from 1 (not at all) to 7 (completely).

Experimental Protocol

The Procedure for the VR Part

Table 7 provides a summary of the experimental protocol. At a sound and light controlled lab, participants were shown how to use the touch controller and were given instructions on the experimental protocol. The participants wore two smart watches. We measured participants' arm cuff heart rate and double checked that the two smart watches matched the readings on the arm cuff device. The remainder of the protocol will be explained in phases.

Baseline*:* Participants completed their demographic questions, and recorded baseline measures of trait anxiety, trait social anxiety, communication apprehension, paranoia, depression, and maths anxiety. They also completed baseline state measures of mood, panic symptoms, anxiety sensitivity, and state anxiety (GAD-$7_{Modified}$, SUDS) and state social anxiety ($SASCI_{Modified}$) via Qualtrics on the lab desktop.

Anticipation: Upon completion of the baseline measures, participants put on the VR headset. The task instructions were shown on the VR display (preparation for three minutes). Participants then recorded how anxious they were (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$) while both Groups were facing an empty room. Then, a three-minute talk about the future of artificial intelligence (AI) and its disadvantages and benefits was left on the screen. A countdown timer was available. For those who were assigned to the Group with an audience, the audience entered the room halfway through and occupied pre-determined seats and started chatting in low tones with one another (Figure 13, panels A and B). During the final 15 seconds of the three minutes of preparation, the audience began to pay greater attention. That is, they adjusted their posture to seem ready to listen to the talk, peered directly into the camera, and the spotlights were slightly dimmed (Figure 13,, panel C).

Table 7

Summary of the Experimental Protocol

Phase	Protocol Description	Device
Baseline	Baseline measures (demographics, maths anxiety, trait anxiety, trait social anxiety, communication apprehension, paranoia, depression), and pre-measures (mood, anxiety sensitivity, panic sensitivity, state anxiety), and state social anxiety (GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$) recorded.	Qualtrics
Anticipation	Speech preparation for three minutes. GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$ recorded **before** speech preparation.	VR
Speech	Speech for three minutes. GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$ recorded **before** and **after** speech.	VR
Recovery	Post measures (GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$) and exploratory measures (mood, anxiety sensitivity, panic sensitivity, performance evaluations, post-event ruminations, VR presence), AI knowledge, and VR experience recorded.	Qualtrics
Break	15 min waiting period in another lab room. At the end of the waiting period, two experimenters enter the room.	NA
Baseline	Pre-measures (GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$) recorded.	Laptop
Instructions	Instructions are revealed. GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$ recorded **after** instructions.	Laptop
Task	Ten basic maths calculation questions. GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$ recorded **after** the task.	Laptop

Note. GAD-7 (Generalised Anxiety Disorder Assessment). SUDS (Subjective Units of Distress Scale). SASCI (Social Anxiety Session Change Index).

Speech: The instructions on the VR teleprompter informed participants that the talk would begin shortly. Participants were told that their speech would be recorded for analysis[7]. Participants recorded how anxious they were right before their talk (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$). For three minutes, participants delivered their rehearsed talks in virtual settings. The topic on the teleprompter was no longer present, but the timer, which was set to run for a further three minutes, was still accessible. Participants again recorded their anxious arousal (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$) in VR following their speech delivery. Once the talk was completed, participants removed the VR headset and notified the experimenter. The responses in VR were recorded using the Bluetooth touch controller. The tasks during the Anticipation and Speech were performed while the participants were standing.

***Recovery*:** Participants used the lab desktop to record their post state anxiety (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$) on Qualtrics as well as their post levels of mood, anxiety sensitivity, and panic symptomology. Participants also completed the questionnaire measures of performance evaluations, post-event processing and presence felt during the speech performance in VR, along with participants' familiarity with the topic of their talk (AI) and their experience with VR headsets.

The Procedure for the Face-to-Face Part

As seen in Table 7, the in-person socially evaluative task consisted of three stages (see Figure 14 for a screenshot of the in-person scene):

Baseline: After being led to another lab room, participants waited for 15 minutes while the effects of the VR task subsided. Two researchers – who were unfamiliar to the participant – entered the room after the waiting period as panel members. Participants completed their baseline assessments of state anxiety (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$) on a laptop using Qualtrics before receiving task instructions.

Instructions: Participants were informed that the session would be recorded (a video camera and audio recorder were placed in the room beforehand). Participants gave permission for the audio and video recording. Participants recorded their state anxiety (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$) using a laptop provided.

Task: Participants verbally responded to 10 simple maths problems. If they made a mistake, they were asked to amend their response. The panel members moved on to the next question after their third error to a question, or when participants remained silent for more than 15 seconds after a question. Following the socially evaluative task, participants recorded their state anxiety (GAD-$7_{Modified}$, SUDS, $SASCI_{Modified}$). Upon completion, the

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[7] Although participants were told that their performance was being recorded, the audio recording data could not be obtained due to technical problems.

Figure 14

Example Scene from the Face-to-Face Part of the Experiment

Note. Participants were seated in (A) while two experimenters sat in (B) and (C). The face-to-face socially evaluative task took place in the presence of a video camera placed on a tripod (D) and a voice recorder (E). Participants' responses were recorded using the laptop (F).

participants were debriefed. See Appendix D for the in-person task instructions and basic calculations.

Data Analytic Strategy

All of the statistical analyses were performed using R Software, version 4.2.0. (R Core Team, 2022). Demographic differences were analysed using one-way Analysis of Variances (ANOVAs). We reported Greenhouse-Geiser corrected degrees of freedom due to the lack of sphericity of our within-subject variable. We employed linear mixed-effects models that allow convenient specification of mixed ANOVAs using the package 'afex' (Singmann et al., 2022) to run our omnibus models. We assessed the change on self-reported anxiety ($GAD\text{-}7_{Modified}$, SUDS, $SASCI_{Modified}$) and heart rate, with 'Time' and 'Group' being entered as fixed effects and participants entered as random effects (error term). For exploratory purposes, we were interested in whether trait social anxiety predicts subjective anxious arousal as opposed to trait generalised anxiety during our 360° photorealistic virtual public speaking paradigm. We created linear mixed-effects models including the interaction terms Time*Group*Trait Social Anxiety and Time*Group*Trait

Generalised Anxiety as fixed effects with participant included as random effects.[8] Both continuous trait measures (SPIN for trait social anxiety and GAD-7 for trait generalised anxiety) were centred on the mean prior to running the analysis. The model took the form of:

State Anxiety (GAD-$7_{Modified}$) ~ 1 + Time + Group + SPIN + GAD7 + Time*Group + Time:SPIN + Time:GAD7 + Group:SPIN + Group:GAD7 + Time: Group: SPIN + Time: Group: GAD7 + (1 | Participant ID)

We used the 'emmeans' and 'emtrends' functions of the 'emmeans' package (Lenth et al., 2018) for decomposition of the interaction effects that included categorical and continuous variables, respectively. We probed the significant main effects via pairwise tests with customised consecutive contrasts. We adjusted the *p* values using the Bonferroni correction for follow-up pairwise tests. Follow-up tests for which we had specific directional hypotheses were one-tailed to improve statistical power, and the rest were two-tailed. Two tailed independent t-tests were computed (adjusted for assuming unequal variances) to investigate the group differences on exploratory outcome measures (performance evaluations, post-event processing, VR presence).

Heart Rate Data. The sampling frequency of the Fitbit Charge 2 is five seconds under ideal conditions and ranges from five seconds to 15 seconds, dependent upon the Fitbit itself. Data were acquired using the Application Programming Interface (API) provided by the Fitbit manufacturers. The extracted Fitbit data (timestamps provided based on Network Time Protocol, GMT +1) were matched with the experimental task start and end time and date, which were manually recorded in seconds for each participant on that particular experiment day. We mirrored the VR screen into another device via TeamViewer (https://www.teamviewer.com/en/) to record the precise start and end times. Because the sampling frequency is dependent on the Fitbit itself, we created missing values (NAs) in the dataset at a one-second level per participant per key event. Although Fitbit brand activity trackers are more frequently utilised in validation studies as well as in clinical trials compared to other-branded wearables (Henriksen et al., 2018), potential noise in the data might arise due to motion artifacts or signal crossover (Bent et al., 2020). To our knowledge, no filtering exists in the literature for short term PPG signals (e.g., < three mins), while a significant amount exists for longitudinal data (e.g., (O'Driscoll et al., 2020)). We therefore applied a rolling average with a window size of two, which takes four true observations to both sides (two left, two right) into consideration to smooth the data, using the 'imputeTS' package in R (Moritz & Bartz-Beielstein, 2017). The data were then

[8] For this analysis, Time factor included three levels of Anticipation, before Speech, and after Speech, that was recorded within our VR paradigm. Refer to Table 7 for a summary of the experimental protocol.

aggregated over time periods which corresponded to key events in the experiment. The key events in the VR task were Baseline, Anticipation, Talk, and Recovery. We averaged three-minute periods from each phase (for Baseline and Recovery, we took an average of the last three minutes of that particular phase). The key events for the face-to-face task were Baseline and Task. Baseline corresponds to the final one minute of the participants' wait period before the panel members entered the room. Because the time duration for the Task phase varied per participant (minimum time spent = 1 minute 20 seconds, $M_{time\ spent}$ = 1 minute 51 seconds, $SD_{time\ spent}$ = 39 seconds), we averaged the heart rate over the first minute of the Task when the instructions were revealed and whilst the basic calculations were performed. We then submitted the averaged heart rate values into linear mixed-effects models to investigate Group*Time interaction for the VR and the face-to-face tasks using the above-mentioned R packages. To note, one participant (in the Group who participated in empty virtual halls) removed their smart watches during the face-to-face part of the experiment, so their data is excluded from the heart rate analysis for the face-to-face task.

Results

Group Characteristics

Table 8 provides a summary of the group characteristics for the demographic data. In general, the groups consisted of young adults, who predominantly described themselves as white and did not differ in age, gender, nor education status. The group differences on the baseline measures are presented in Table 9. Groups were comparable on all baseline measures. Both groups displayed high levels of social anxiety, scoring higher than the clinical cut-off value of 19 on the SPIN (Connor et al., 2000).

Main Analysis: Subjective Anxious Arousal During the VR Task and Subsequent Face-to-Face Task

To investigate self-reported subjective anxious arousal during the public speaking task in VR, separate 2 (Group: Audience, No Audience) x 5 (Time: Baseline, Anticipation, before Speech, after Speech, Recovery) linear mixed-effects models were run on state anxiety (GAD-$7_{Modified}$, SUDS) and state social anxiety ($SASCI_{Modified}$). The main effect of Group was not significant on any outcome measures (*p*s> .507, *F*s < 0.45, η2ps < .007). There was a significant main effect of Time on all state anxiety and state social anxiety, *p*s < .001, *F*s > 9.98, η2ps > .139. Figure 15 (top panel) displays the increase with a peak before Speech, followed by decreases in the reported anxious arousal until Recovery (see Table 10 for follow up test statistics). There were no significant interaction effects of Group*Time on self-reported state anxiety (GAD-$7_{Modified}$, SUDS), *F*s < 1.19, *p*s > .314, η2ps < .019, but the interaction effect was significant for the state social anxiety scores ($SASCI_{Modified}$), *F*(2.80, 173.70) = 3.94, *p* = .011, η2p = .060 (see Table 10 for the omnibus test statistics and Table 11 for the observed means and standard deviations for

Table 8

Group Characteristics: Demographics

	Audience Present			Audience Absent			
	n	M	*SD*	n	M	*SD*	Test
Gender	32			32			$\chi 2 = 0$, $p > 0.10$
…Female	18	56%		17	53%		
…Male	14	44%		15	47%		
Age	32	24.88	8.58	32	25.75	5.91	$t(55.01) = 0.47$, $p = .636$
Ethnicity	32			32			$\chi 2 = 2.378$, $p > 0.10$
…White	20	62%		16	50%		
…Black	2	6%		1	3%		
…Asian	6	19%		9	28%		
…Mixed	3	9%		3	9%		
…Other	1	3%		3	9%		
Education	32			32			$\chi 2 = 5.867$, $p > 0.10$
…Less than high school degree	1	3%		0	0%		
…High school degree	12	38%		8	25%		
…Bachelor's degree	6	19%		7	22%		
…Master's degree	8	25%		13	41%		
…Doctoral degree	1	3%		3	9%		
…Other	4	12%		1	3%		
VR Experience (0-10)	32	2.56	2.46	32	2.81	2.64	$t(56.97) = 0.11$, $p = .909$
AI Knowledge (0-4)	32	1.47	1.24	32	1.50	0.92	$t(61.68) = 0.39$, $p = .697$
In-person Task Duration (seconds)	32	105.15	24.81	32	117.81	49.17	$t(45.82) = 1.30$, $p = .200$

Note. AI = Artificial Intelligence. VR = Virtual Reality. For t-tests, degrees of freedom (df) were adjusted for not assuming equal variances.

Table 9

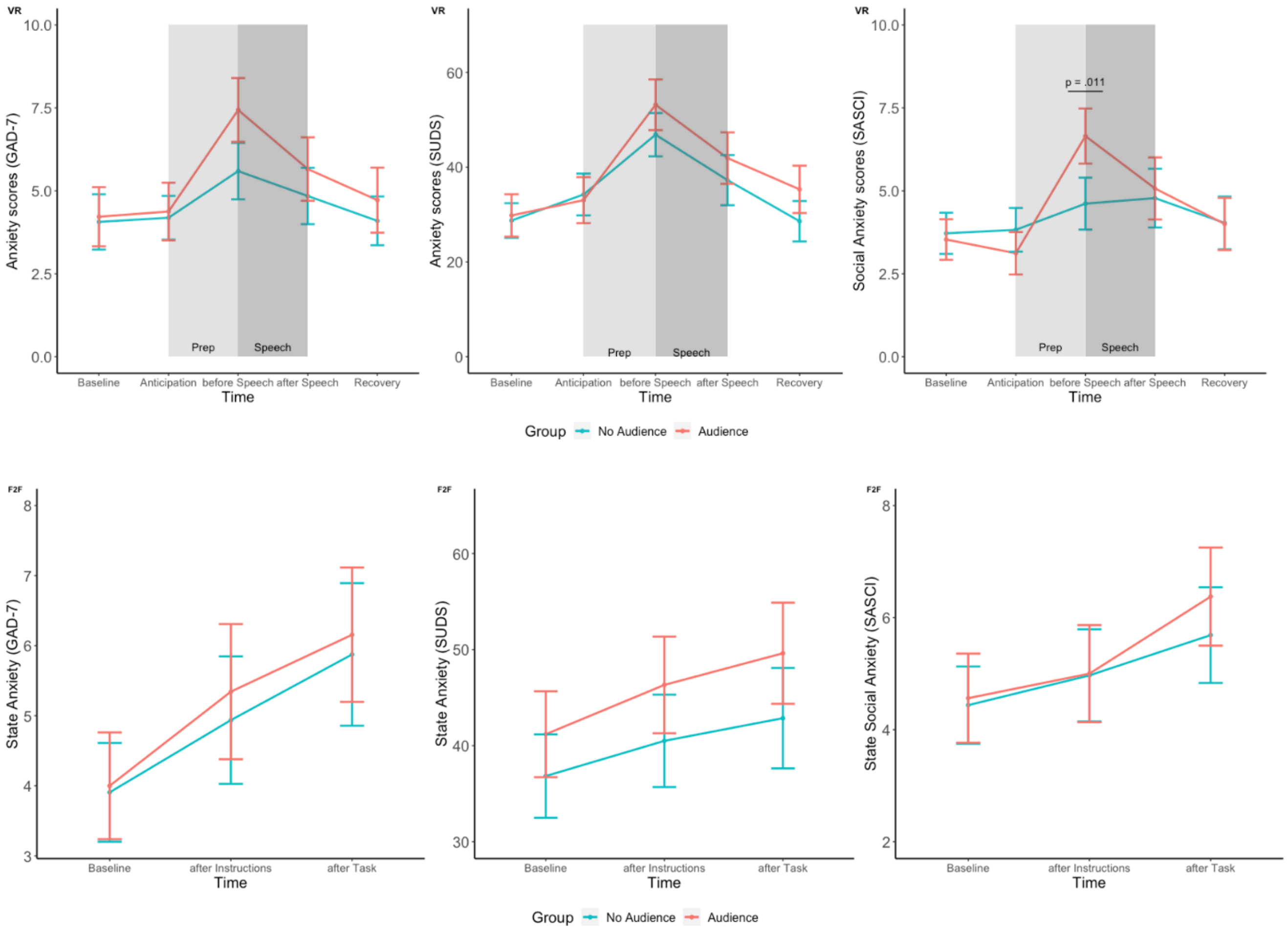
Group Characteristics: Baseline Scores

	Audience Present (n = 32)		Audience Absent (n = 32)		
	M	*SD*	M	*SD*	Test
Math Anxiety (AMAS)	21.16	7.22	18.97	5.84	$t(59.40) = 1.33$, $p = .188$
Generalised Anxiety (GAD-7)	6.81	5.32	6.59	4.17	$t(58.68) = 0.18$, $p = .855$
Social Interaction Fear (SIAS)	29.34	11.86	30.12	12.37	$t(61.89) = 0.26$, $p = .797$
Social Anxiety SPIN)	21.72	14.70	23.09	12.09	$t(59.78) = 0.41$, $p = .684$
Social Anxiety (LSAS)	49.75	27.45	46.69	25.01	$t(61.47) = 0.47$, $p = .642$
Communication Apprehension	21.28	4.81	21.47	5.45	$t(61.06) = 0.15$, $p = .884$
Paranoia (R-GPTS)	6.66	8.40	3.66	4.76	$t(49.05) = 1.76$, $p = .085$
Depression (PHQ-9)	8.31	6.25	8.66	5.12	$t(59.67) = 0.24$, $p = .811$

Note. AMAS (Abbreviated Math Anxiety Scale), GAD-7 (Generalised Anxiety Disorder Assessment), SIAS (Social Interaction Anxiety Scale), SPIN (The Social Phobia Inventory), LSAS (Liebowitz Social Anxiety Scale), R-GPTS (The Revised Green et al. Paranoid Thoughts Scale), PHQ-9 (Patient Health Questionnaire-9). Communication Apprehension is recorded using PRCA-24 24 (The Personal Report of Communication Apprehension). Degrees of freedom (df) were adjusted for not assuming equal variances among between-subjects groups.

Figure 15

Interaction Plots for Self-reported State Anxiety (GAD-7$_{Modified}$, SUDS, SASCI$_{Modified}$) During the VR and Face-to-Face Tasks



Note. Error bars represent standard error (SE). VR = The VR phase. F2F = The face-to-face phase.

Table 10

Test Statistics of Omnibus Models and Follow-up Tests of Time on the Self-Reported Anxious Arousal During the VR Task

	State Anxiety / GAD-7*Modified*			State Anxiety / SUDS			State Social Anxiety / SASCI*Modified*		
	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p
Group	(1, 62), 0.45	.507	.070	(1, 62), 0.35	.557	.006	(1, 62), 0.08	.774	.001
Time	(3.23, 200.4), 9.98	**< .001**	.139	(2.85, 176.53), 22.15	**< .001**	.263	(2.80, 173.70), 12.18	**< .001**	.164
Group X Time	(3.23, 200.4), 1.19	.314	.019	(2.85, 176.53), 0.97	.406	.015	(2.80, 173.70), 3.94	**.011**	.060

Change in Time	*t*(62)	Lower Upper 95% CI	*p*	*d*	*t*(62)	Lower Upper 95% CI	*p*	*d*
T1 to T2	0.364	[-0.85, 1.13]	.999	0.03	2.37	[-0.37, 9.09]	.083	0.17
T2 to T3	5.99	[1.27, 3.19]	**<. 001**	0.47	8.18	[11.23, 21,52]	**< .001**	0.60
T3 to T4	-2.96	[-2.36, -0.17]	**.017**	0.25	-3.70	[-17.67, -3.17]	**.002**	0.35
T4 to T5	-2.23	[-1.87, 0.13]	.117	0.16	-3.68	[-12.98, -2.29]	**.002**	0.27

Note. T1 = Baseline, T2 = Anticipation, T3 = Before Speech, T4 = After Speech, T5 = Recovery. See Table 7 for a summary of the protocol and time points. Effect size of partial eta squared (η2p) is reported for main effects and interactions, and *d* $(M2 - M1)/SD_{pooled}$ is reported for pairwise comparisons. The follow-up tests for the SASCI*Modified* outcome are not reported due to a higher order significant effect.

Table 11

Observed Means and Standard Deviations of Group Across Time for the Reported Anxious Arousal During the VR Task

Measure	Audience Present *n* = 32				
	Baseline	Anticipation	Before Speech	After Speech	Recovery
	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)
GAD-7*Modified*	4.22 (5.05)	4.38 (4.91)	7.44 (5.44)	5.66 (5.41)	4.72 (5.55)
SUDS	29.8 (25.3)	33.01 (27.5)	53.20 (30.30)	41.90 (30.7)	35.3 (28.3)
SASCI*Modified*	3.53 (3.46)	3.12 (3.62)	6.65 (4.69)	5.07 (5.29)	4.00 (4.45)
	Audience Absent *n* = 32				
	Baseline	Anticipation	Before Speech	After Speech	Recovery
	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)
GAD-7*Modified*	4.06 (4.72)	4.19 (3.73)	5.59 (4.81)	4.84 (4.81)	4.09 (4.16)
SUDS	28.70 (20.7)	34.20 (24.90)	46.80 (25.90)	37.2 (29.9)	28.6 (24.1)
SASCI*Modified*	3.72 (3.51)	3.82 (3.73)	4.61 (4.43)	4.78 (5.01)	4.03 (4.50)

GAD-7*Modified*, SUDS and SASCI*Modified*). As evident in Figure 15 (top panel, grey-shaded areas), in contrast to individuals who performed in virtual lecture halls with no audience, performing in front of an audience in our photorealistic VR paradigm led to a more rapid increase in anxiety across three self-reported state anxiety measures before the participants delivered their Speech. Though small effects for GAD-7*Modified*, SUDS, these trends were significant and more pronounced on self-reported *state social anxiety*. Upon breaking down the significant interaction effect on state social anxiety, simple effects analyses revealed no significant Group differences at Baseline, $F(1, 62) = .046$, $p = .830$, n2p = .001, $M_{diff} = 0.187$, at Anticipation ($F(1, 62) = .592$, $p = .444$, n2p = .009, $M_{diff} = 0.707$), after Speech ($F(1, 62) = .051$, $p = .822$, n2p = .001, $M_{diff} = 0.291$), and at Recovery ($F(1, 62) = .001$, $p = .978$, n2p < .001, $M_{diff} = 0.031$). Before Speech, the group differences were small ($F(1, 62) = .3.17$, $p = .079$, n2p = .049, $M_{diff} = 2.04$), which was in line with the visual trend in Figure 15 (top right), where people who were exposed to an audience in our photorealistic VR paradigm felt higher *social anxiety* than those who prepared a talk in an empty virtual room.

To investigate the impact of the photorealistic VR exposure on a subsequent *in-person* socially evaluative task on state anxiety levels, separate 2 (Group: Audience, No Audience in VR) x 3 (Time: Baseline, *after* Instructions, *after* Task) linear mixed-effects models were run on state anxiety ($GAD\text{-}7_{Modified}$, SUDS) and state social anxiety ($SASCI_{Modified}$). There were no main effects of Group (Fs<0.75, ps>.391, η2ps<.012). The main effect of Time was significant on all outcome measures (Fs > 7.54, ps <.002, η2ps>.108). The general pattern revealed increased self-reported anxious arousal until the end of the Task over Baseline levels. See Table 12 for the follow up tests for Time). However, the significant main effects of Time did not qualify significant interaction effects of Group*Time on any outcome measures (Fs <0.67, ps>.490, η2ps <.011, see Table 12 for test statistics for omnibus models). That is, looking at Figure 15 (bottom panel), a subsequent in-person socially evaluative task produced a significant increase in self-reported anxious arousal irrespective of prior exposure to an audience in our photorealistic VR paradigm. Taken together, our data provide partial evidence of a general anxiogenic effect of a photorealistic and pre-recorded virtual environment, however it indicates a relevance of our paradigm to situational social anxiety. However, it is important to note that, according to our sensitivity analysis, our study could reliably detect effects with η^2 values of 0.115 and above. Our subjective anxiety measures ($GAD\text{-}7_{Modified}$ and SUDS) had η^2 values of 0.04 and 0.03 for interaction effects, respectively (converted from n2p values presented in Table 10, as G*Power only provides sensitivity effects in η^2). This suggests that the study may not have reliably captured our observed effects for subjective anxious arousal for the interaction findings. However, we observed an η^2 value of 0.12 for the social anxiety outcome variable ($SASCI_{Modified}$). This might give confidence in detecting the actual true effects, considering that the obtained effect size of $SASCI_{Modified}$ exceeded the size our study can detect within the current sample size.

Main Analysis: Objective Anxious Arousal (Heart Rate) During the VR Task and the Subsequent Face-to-Face Task

To study the agreement of the two smart watches, we ran concordance class correlation (CCC) analyses using the ‘epiR’ package (Stevenson et al., 2018). CCC estimates the agreement of two variables for inter-rater reliability (Lin, 1989). In line with the previous research, the strength of the agreement was interpreted based on the following: weak (CCC<.5), moderate (CCC = .5 - .7), and strong (CCC>.7) (Nelson & Allen, 2019). The analyses were computed on the rolling average with a window size two of each Time phase (i.e., ‘Baseline’, ‘Anticipation’, ‘Speech’, ‘Recovery’). Based on the CCC analyses, there was a strong measurement agreement between the two watches at Baseline (CCC = .916 95%CI [.866, .948]) and at Recovery (CCC = .844 95%CI [.759, .901]), and a moderate agreement during the Anticipation phase (CCC = .767 95%CI [.647, .850]) and the Speech phase (CCC = .686 95%CI [.545, .788]) for the VR phase of the experiment. Likewise, there was a strong agreement between the two

Table 12

Test Statistics of Omnibus Models and Follow up Tests of Time for the Face-to-face Task

	State Anxiety / GAD-7$_{Modified}$			State anxiety / SUDS			State Social Anxiety / SASCI$_{Modified}$		
	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p
Group	(1, 62), 0.05	.824	.001	(1, 62), 0.75	.391	.012	(1,62), 0.06	.800	.001
Time	(1.62, 100.49), 11.73	**<.001**	.159	(1.58, 97.90), 7.54	**.002**	.108	(1.72, 106.35), 13.11	**<.001**	.175
Group X Time	(1.62, 100.49), 0.07	.901	.001	(1.58, 97.90), 0.21	.759	.003	(1.72, 106.35), 0.67	.490	.011

Change in Time	*t*(62)	Lower Upper 95% CI	*p*	*d*	*t*(62)	Lower Upper 95% CI	*p*	*d*	*t*(62)	Lower Upper 95% CI	*p*	*d*
Baseline to Instructions	3.18	[0.33, 2.04]	**.004**	0.25	3.07	[1.11, 7.68]	**.006**	0.17	2.05	[-0.06, 1.03]	.089	0.11
Instructions to after Task	2.36	[0.02, 1.73]	**.043**	0.16	1.55	[-1.36, 7.02]	.252	0.10	3.20	[0.30, 1.80]	**.004**	0.22

Note. See Table 7 for a summary of the protocol and time points. Effect size of partial eta squared (η2p) is reported for main effects and interactions, and *d* ($M2 - M1$)/SD_{pooled} is reported for pairwise comparisons.

watches at Baseline (CCC = .962, 95%CI [.938, .976]) and at Task (CCC = .937, 95%CI [.898, .961]) during the face-to-face socially evaluative task. Given moderate to strong agreements between the two watches at both the VR and face-to-face parts of the experiment, we averaged the heart rate data of the two watches over time periods to run our main analyses.

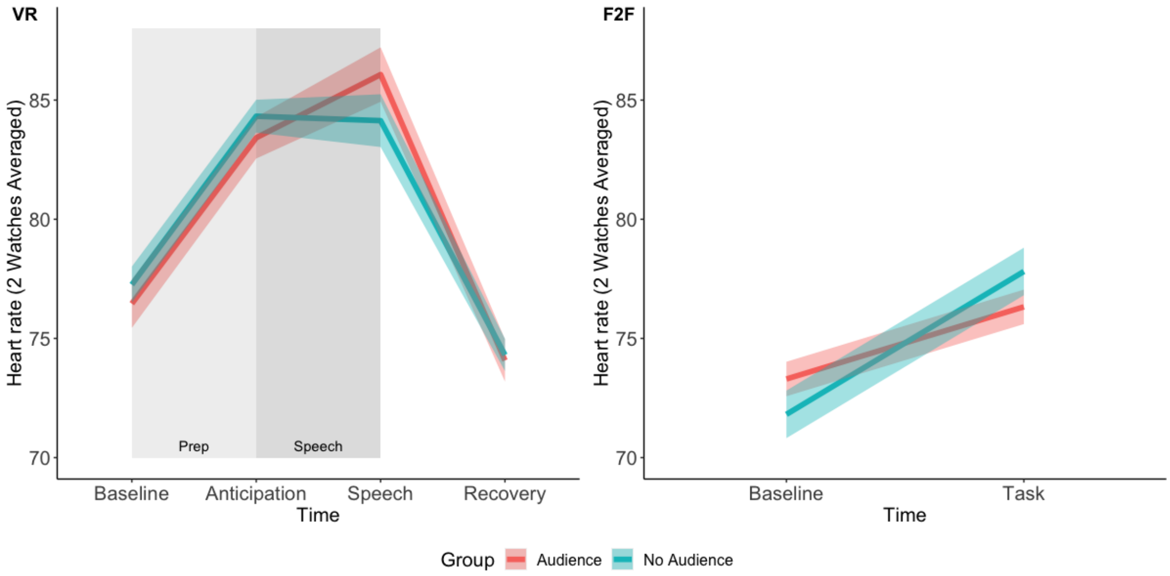
To investigate the change in heart rate levels during the VR task, a 2 (Group: Audience VR, No Audience VR) x 4 (Time: Baseline, Anticipation, Speech, Recovery) linear mixed-effects model was run. There was a significant main effect of Time, $F(2.12, 131.23) = 68.41$, $p < .001$, n2p = .525. Follow-up tests revealed that participants' heart rate levels increased from Baseline to Anticipation, $t(62) = 8.11$, $p < .001$, Cohen's d = 0.56, $M_{diff} = 7.00$, and remained elevated from Anticipation to Speech, $t(62) = 1.47$, $p = .438$, Cohen's d = 0.09, $M_{diff} = 1.20$, followed by a significant decrease until Recovery, $t(62) = 10.43$, $p < .001$, Cohen's d = 0.88, $M_{diff} = 10.90$. There was no significant main effect of Group, $F(1, 62) = 1.54$, $p = .219$, n2p = .024, and no significant interaction of Time*Group, $F(2.12, 131.23) = 1.06$, $p = .352$, n2p = .017. Table 12 displays the omnibus test statistics and follow-up test statistics. Although no significant interaction was observed, Figure 16 (left panel) suggests that performing in the presence of an audience increased self-reported anxious arousal (i.e., a steeper slope with an increasing trend) during Speech.

To investigate the change in heart rate levels during the subsequent face-to-face task, a 2 (Group: Audience in VR, No Audience in VR) x 2 (Time: Baseline, Task) linear mixed-effects model was run. There was a significant main effect of Time, $F(1, 61) = 27.13$, $p <.001$, n2p = .308. All participants' heart rate levels increased during Task (M = 77.1, SD = 11.5) relative to Baseline (M = 72.6, SD = 10.5), $t(61) = 5.41$, $p <.001$, d = 0.41. There was no significant main effect of Group, $F(1, 61) = 0.33$, $p = .566$, n2p = .005, and no significant interaction, $F(1, 61) = 2.93$, $p = .092$, n2p = .046. Despite null findings, visual inspection of Figure 16 (right panel) suggests that having performed in a photorealistic virtual hall with a pre-recorded audience (as opposed to performing in an empty virtual lecture hall) might reduce anxious arousal in a subsequent socially evaluative in-person task (i.e., a gentler increasing slope was observed for those who performed in our photorealistic virtual hall with a pre-recorded audience as opposed to performing in an empty virtual hall). See Table 13 for observed means and standard deviations, effect sizes, and increases/decreases in percent for the differences in heart rate levels over baseline for both the VR and in-person tasks.

Taken together, our data suggest that our paradigm might have the potential to produce physiological arousal. That is, looking at Table 8, over baseline, performing in front of a pre-recorded audience in our photorealistic VR paradigm resulted in a 12% increase in heart rate levels, whilst this was 9% if the performance was in an empty virtual

Figure 16

*Heart Rate Change During the VR Task and Face-to Face Task of the Experiment for Group*Time Interaction*



Note. The shaded areas of the lines represent the lower and upper limits (1.96) of the standard error (SE).

Table 13

Observed Means and Standard Deviations, Effect Sizes, and Increases/Decreases in Percent for the differences in HR over Baseline During the VR and Face to Face Parts of the Experiment

	VR Task *N* = 64						Face-to-Face Task *N* = 63					
	Audience Present *n* = 32			Audience Absent *n* = 32			Audience Present *n* = 32			Audience Absent *n* = 31		
	M (SD)	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%	*M (SD)*	*d*	%
Baseline	78.3 (13.00)	-	-	75.5 (10.8)	-	-	72.5 (10.6)	-	-	72.6 (10.7)	-	-
Anticipation	85.2 (14.4)	0.50	+ 8.10	82.5 (11.7)	0.62	+ 9.27	-	-	-	-	-	-
Speech / Math Task	87.9 (15.1)	0.68	+ 12.26	82.3 (11.6)	0.61	+ 9.01	75.6 (10.6)	0.29	+ 4.27	78.6 (12.3)	0.52	+ 8.26
Recovery	75.9 (12.2)	0.19	- 3.06	72.5 (9.71)	0.29	- 3.97	-	-	-	-	-	-

Note. + = increase, - = decrease. See Table 7 for a summary of the protocol and time points. Effect size of *d* ($M2 - M1$)/SD_{pooled} is reported.

hall. Likewise, the translational effect of our VR paradigm into anxiogenic real-life settings suggested numerical success. As per Table 8, exposure to our VR paradigm was able to double the habituation effect (in percentage) on objective anxious arousal during a subsequent socially evaluative task performed in person. We run a supplementary analysis to further breakdown the control group (No Audience) into those who did versus did not have an anxious response to the empty room and investigated anxiogenic subjective reactions during the in-person socially evaluative task. The findings did not affect the interpretation of our findings and presented in Appendix E as supplementary analysis.

Exploratory Analyses

Associations between Trait Measures and Peak Anxious Responses to VR and Face-to-Face Task

We performed Pearson's *r* correlations to examine the relationship between trait measures and peak social evaluation induced anxious reactivity. We had one person's heart rate data missing from the face-to-face part of the task. In the correlation model, we specified pairwise complete observations, meaning that the correlation between each pair of variables is computed using all complete pairs of observations on those variables. We divided our data by Group and conducted separate correlation analyses for each Group (Audience, No Audience).

Figure 17 displays strong positive correlations between trait anxiety (social and generalised) for each Group, *r*s> 0.42, *p*s < .015. Additionally, trait anxiety for both Groups showed significant positive associations with depression, *r*s> 0.44, *p*s < .012, and math anxiety, *r*s> 0.39, *p*s < .028. Trait anxiety was not associated with trait paranoia for both Groups, *r*s< 0.32, *p*s > .074.

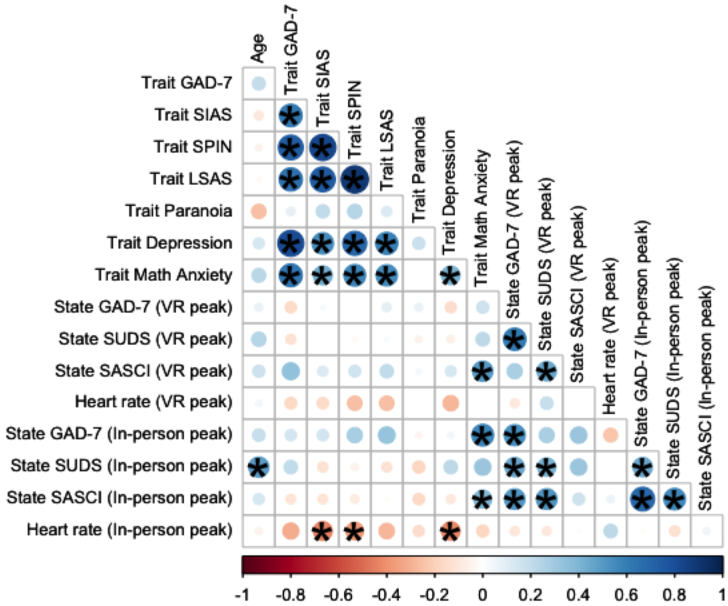
In the 'No Audience' Group, there was a positive association between state SPIN and peak in-situ subjective anxiety that was induced during the VR task (SUDS), *r* (30) = 0.46, *p* = .009. However, this effect was not observed in the Audience group that saw the virtual audience, *r* (30) = -0.03, *p* = .874. In addition, we observed that situational peak subjective social anxiety that was induced during VR task was positively associated with trait math anxiety only in the Audience group, *r* (30) = 0.50, *p* = .003, and with trait paranoia only in the No Audience group, *r* (30) = 0.44, *p* = .011.

Regarding in-situ peak arousal, the group that performed to a photorealistic audience showed a significant *negative* correlation between trait social anxiety (SPIN and SIAS) and peak heart rate during the in-person social task, *r*s> 0.37, *p*s < .034. Additionally, trait depression was also *negatively* correlated with peak heart rate during the in-person social task, *r* (30) = -0.42, *p* = .016. These effects were not observed in the No Audience group, *r*s< 0.24, *p*s > .0192.

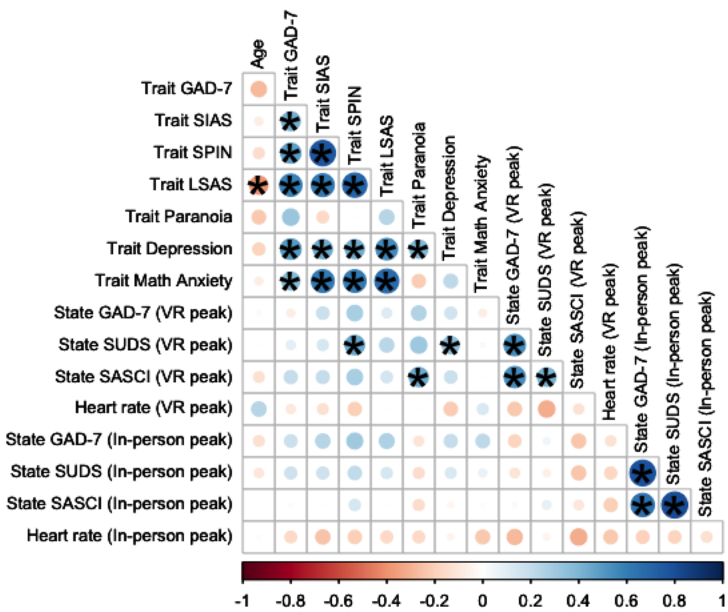
Figure 17

Correlations Between Trait Measures and Social Evaluation Induced Subjective and Objective Responses

Group: Audience



Group: No Audience



Note. * denotes $p < .005$. The bottom analogue scale represents Pearson's r values, with red indicating negative associations and blue indicating positive associations. The size of the circles represents the magnitude of the r values, with larger circles indicating higher values.

Relating 360° Photorealistic VR paradigm to *Trait* Social Anxiety

We did not detect a three-way interaction for both Time:Group:SPIN and Time:Group:GAD7 (*F*s < 1.84, *p*s > .163). However, the two-way interaction of Group:SPIN showed a borderline significant trend, $F(1, 58) = 2.89$, $p = .094$, whereas the interaction effect of Group:GAD7 was highly insignificant, $F(1, 58) = 1.83$, $p = .181$. Looking at the left panel in Figure 18, simple slope analyses for Group:SPIN revealed that high trait *social* anxiety scores predicted more subjective anxious arousal when exposed to a photorealistic audience in VR, $t(58) = 4.12$, $p < .001$; however, the increase in the reported subjective anxious arousal could not be predicted from trait social anxiety when performing in an empty yet photorealistic virtual lecture hall, $t(58) = 1.96$, $p = .060$. This exploratory analysis illustrates the potential relevance of the situational anxiogenic effect to *trait* social anxiety when performing in a socially evaluative virtual lecture hall.

Anxiety Sensitivity, Panic Symptoms and Mood during VR Task

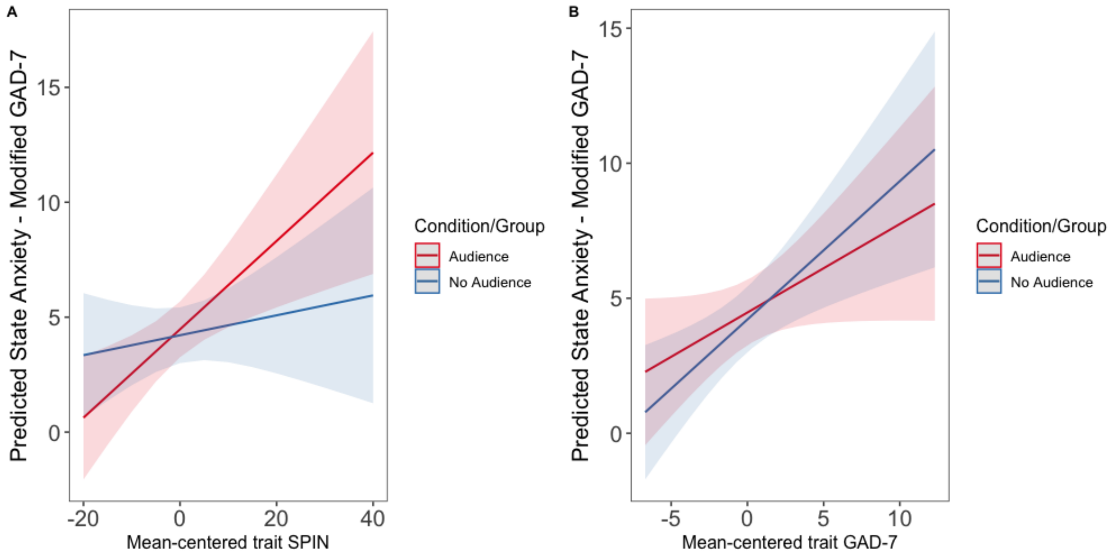
Separate 2 (Group: Audience, No Audience) x 2 (Time: Time1/Baseline, Time5/Recovery) linear mixed-effects models were run with PANAS (Positive Affect and Negative Affect), ASI (Anxiety Sensitivity Index), and PSI (Panic Symptom Inventory) as dependent variables. None of the effects reached significance (*F*s <2.00, *p*s > .162, η2ps <.031). However, looking at Figure 19, visual trends suggested an overall decrease in anxiety sensitivity levels for both groups, and an increase in the panic-like symptomology and negative mood. The magnitudes of the panic-like symptoms and negative mood were slightly more pronounced (relative to anxiety sensitivity increase and positive mood decrease) when performing in the presence of an audience in VR.

Performance Evaluations, Post-event Processing, VR Presence during VR Task

Separate independent samples t-tests (two-tailed) for Group (Audience, No Audience) were run on the retrospective performance evaluations of participants (from self-perspective and others' perspective), post-event processing (negative ruminations), and the presence experienced in the virtual environment. The groups did not significantly differ on any of the exploratory outcome measures (*t*s < 1.43, *p*s > .157, Cohen's *d*s < 0.36). As per Figure 20, the virtual public speaking experience resulted in comparable degrees of performance evaluations and post-event processing, and both groups reported comparable and high levels of presence. However, the realism reported in virtual environments (measured by the realism subscale of the Presence Questionnaire (Witmer & Singer, 1998)) was significantly different for the two Groups, $t(52.1) = 2.24$, $p = .029$, $d = 0.56$. Looking at Figure 7 (bottom panel), the group who performed facing an audience perceived the virtual environment as more realistic ($M = 32.8$, $SD = 7.12$) relative to those who performed in the empty virtual lecture hall ($M = 27.4$, $SD = 11.4$).

Figure 18

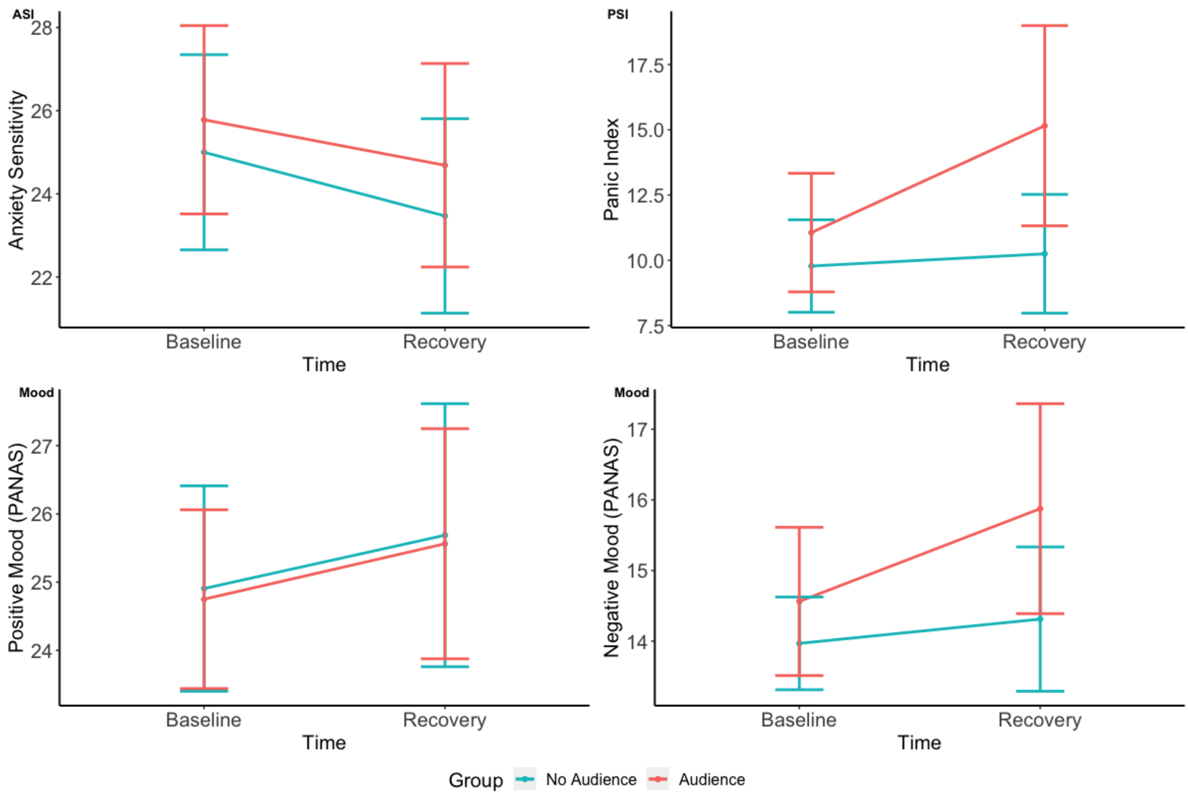
The Effect of Trait Generalised Anxiety and Trait Social Anxiety on Situational Anxiety When Performing in VR



Note. Shaded areas represent standard errors (-1.96, +1.96).

Figure 19

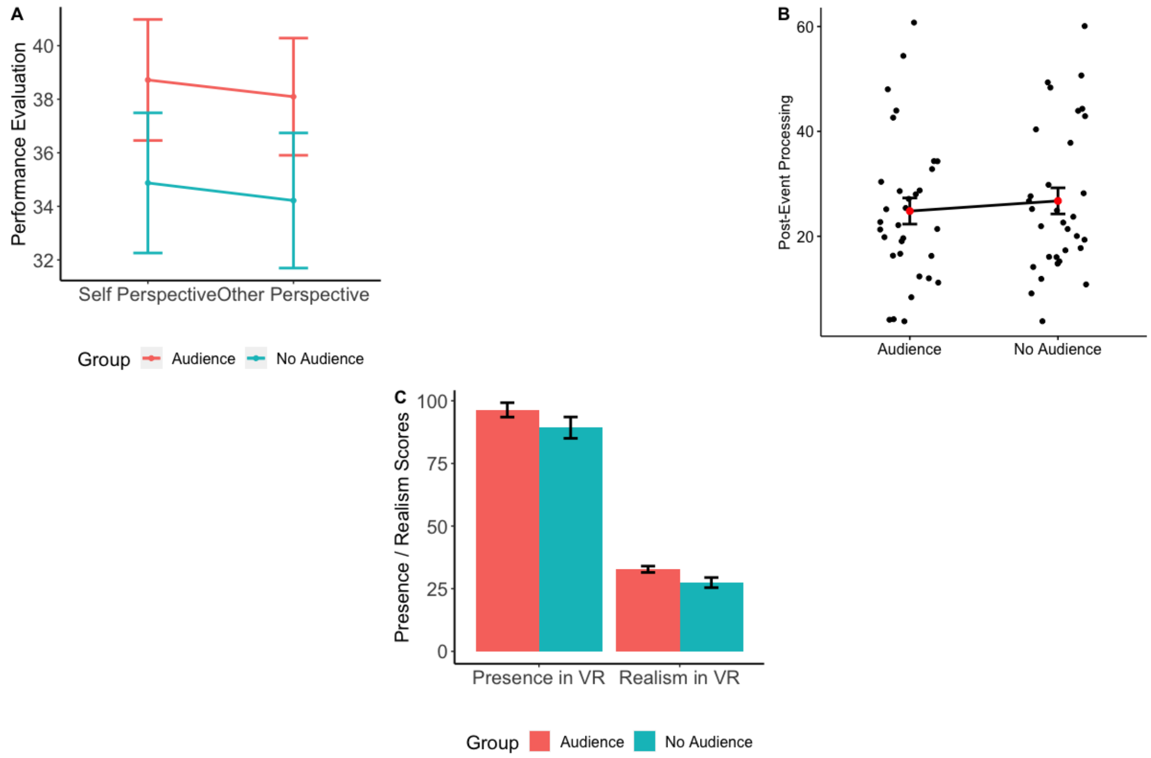
Self-reported Anxiety Sensitivity, Panic Levels and Mood at Baseline and Recovery Phases of the VR Task



Note. Error bars represent standard error (SE). ASI = Anxiety Sensitivity Inventory. PSI = Panic Symptom Index. PANAS = Positive and Negative Affect Scale.

Figure 20

Self-reported Performance Evaluations, Post-event Processing and Virtual Presence Measured in the Aftermath of the VR Task



Note. The higher scores denote better performance evaluations, more severe post-event processing and higher presence. Error bars represent standard error (SE).

Discussion

The aim of this study was first to determine how a photorealistic 360° virtual public speaking paradigm, where socially evaluative stimuli were delivered via a pre-recorded audience, would alter the subjective and objective anxious reactivity that is tested on a nonclinical population. A subsequent verbal mental arithmetic task, performed in front of unfamiliar jury members, was designed to elicit real-life anxious arousal to evaluate further if our 360° VR paradigm would habituate anxious reactivity experienced during this semi-naturalistic anxiogenic real-life task.

Due to the clinical relevance of socially evaluative threat to SAD, we sought to determine whether high trait levels of *social* anxiety as opposed to a general type of trait anxiety (GAD) would predict distinct anxious reactivity within our VR paradigm. We also explored changes in mood, anxiety sensitivity, and panic symptomology, and investigated the group differences on the mechanisms of social anxiety (i.e., performance evaluations, post-event processing), as well as experienced presence in the aftermath of the virtual public speaking performance when faced with an audience or not.

Findings suggested a significant association between performing in the presence of a virtual audience and higher scores of peak state social anxiety recorded during the

VR task. This finding underscores the potential value of using socially evaluative VR paradigms in social anxiety research.

Findings from the 360° VR paradigm

We detected small differences in state anxious arousal when participants performed in the presence vs. absence of a pre-recorded audience. This finding is in line with the previous work that utilised socially evaluative paradigms on non-clinical populations in real-life (Chalmers et al., 2021; Kirschbaum et al., 1993; Schommer et al., 2003), via two-dimensional computer screens (Fallon et al., 2016), within VR (Jönsson et al., 2010; Shiban et al., 2016; Zimmer, Buttlar, et al., 2019; Zimmer, Wu, et al., 2019), as well as via 360-degree paradigms (Schebella et al., 2019). Our paradigm produced a two-fold increase in self-reported state anxious arousal (SUDS, GAD-$7_{Modified}$) over baseline. This effect is superior to a previous virtual public speaking paradigm (13%) where an audience was conveyed via computerised graphics (Kothgassner, Felnhofer, et al., 2016). Levels of peak *objective* anxious arousal over baseline within our paradigm (12.26%, Table 13) indicated findings similar to those reported elsewhere (12-17%) (Jönsson et al., 2010; Wallergård et al., 2011), with comparable effect size (Cohen's d = 0.68) to a recent-meta-analysis that investigated the effectiveness of virtual TSST protocols (van Dammen et al., 2022).

However, our data suggested that performing in an empty photorealistic virtual hall also resulted in considerable degree of subjective (27-38%) and objective (9%) anxious reactivity over baseline, which contradicts with the previous work that employed empty virtual rooms as a control condition within virtual public speaking paradigms (8% in subjective anxious arousal and 1% in objective arousal) (Kothgassner, Felnhofer, et al., 2016) or a virtual TSST paradigm (Zimmer, Buttlar, et al., 2019). Why our empty virtual room produced comparable anxious responses could be due to how we operationalised the 'control' condition. In our design, to minimise group differences, participants were instructed to talk about identical topics (i.e., 'Artificial Intelligence') in the group to which they were assigned, whether speaking in an empty hall or in front of an audience. However, Zimmer, Buttlar, et al. (2019) used a control task inside a virtual TSST paradigm in which participants were allowed to talk about a self-selected topic. Likewise, Kothgassner, Felnhofer, et al. (2016) presented standardised slides to participants behind a speaker's desk throughout the giving of a speech. Dickerson and Kemeny (2004) evidenced that motivated performance tasks *without* a socially evaluative threat component is not necessarily associated with anxious reactivity. Although the abovementioned 'control' tasks still require an immediate cognitive response as part of the motivated performance, as opposed to a passive task such as watching a movie (Blascovich & Mendes, 2001), the demand on the cognitive response might have been reduced with some control over the task (e.g., presenting prepared slides), and therefore might have highlighted the effects previous work has captured as opposed to the hindered effects within our 360° paradigm. In addition, both of our groups (Audience, No Audience) reported high degrees of presence in the aftermath of the 360° VR task. Presence is defined as the degree to which an individual feels linked to or engaged with virtual stimuli or a setting (Schubert et al., 2001; Slater, 1999). The level of presence is thought to be an important element in the success of experimental mood induction (Diemer et al., 2015; Riva et al., 2007), and further has been linked to situational anxiety reactivity during virtual scenarios (Bouchard et al., 2008; Robillard et al., 2003) and during virtual exposure sessions (Ling et al., 2014; Price et al., 2011). Despite the fact that there was a weaker social evaluative element when performing in an empty virtual room, the naturalistic and realistic aspect of the novel 360° technology may have contributed to the participants being fully present in the VR task, leading to anxious feelings for our 'control' group, as well as the group who were exposed to the pre-recorded audience. In addition, prior work has documented that audience size modulates anxious responses during virtual social encounters (Byron et al., 2023; Mostajeran et al., 2020). Therefore, one might also speculate that room size could be a factor to consider in designing the control group, although no studies have examined *room* size aspect. This may have hampered revealing the true effects of our photorealistic VR paradigm, but it does open up possibilities for further investigations into the 360° virtual paradigms and the concept of presence.

Relevance of Situational and Trait Social Anxiety to 360° VR Paradigm

Despite the comparable effects on state anxious arousal, our data provided some evidence on *situational* and *trait social anxiety* moderators in the 360° virtual paradigm. This is consistent with prior research that reported successful situational social anxiety induction within a virtual setting of computerised avatars in a wine bar or on an underground train (James et al., 2003). Together, the findings provide evidence that situational social anxiety can be generated within our novel and practical 360° paradigm can further open the way for explorations of socially evaluative situations within non-clinical populations.

In addition, we found partial evidence that increased trait social anxiety was associated with increased situational anxiety in the paradigm, only when there was a socially evaluative component involved (i.e., audience), and this effect was not observed in another form of trait anxiety (i.e., GAD). This suggests the task is sensitive to individual differences in social anxiety, but not generalised trait anxiety. That is, although both GAD and SAD exhibit anxious reactivity to a threat, this is more related to an internal and ambiguous processing in GAD (e.g., apprehension about any future event) (Duval et al., 2015), whilst SAD pathology is associated with an internal maladaptive processing that is highly dependent on external environmental factors (e.g., apprehension during public speaking) (Heimberg et al., 2010; Rapee & Heimberg, 1997). In addition, this finding aligns with the prior research in which distinct responses were captured for individuals high in SAD (vs controls) within virtual settings (Dechant et al., 2017; Slater et al., 2006), and further indicates the ability of a novel and practical 360° VR technology to be utilised for explorations on SAD symptomology.

Can Anxious Reactivity Observed during VR Exposure Be Generalised to Real Life?

When considering the translational real-life effect of a photorealistic VR exposure, we found evidence of anxiogenic ability during a short and in-person socially evaluative task. However, contrary to our hypothesis, the level of anxiety reactivity within this task did not appear to be influenced by prior exposure to a pre-recorded photorealistic audience in VR. This might be due to the heightened levels of anxious arousal observed in our control task during the VR social evaluation exposure. Given that both the control group and the group that performed in the presence of an audience within the 360° VR paradigm experienced similar levels of heightened anxiety reactivity, it raises questions about whether the observed anxiogenic effects during a real-life social evaluation can be attributed solely to the VR exposure effect. The literature provides limited insight on the prolonged effects of VR exposure to a *real-life* task, and to date no studies examined habituation effects within several virtual exposures with a control group (e.g., (Jönsson et al., 2010; Kotlyar et al., 2008; Schommer et al., 2003)). In a recent study, Kothgassner et al. (2021) investigated the habituation effects of a virtual TSST protocol versus a placebo TSST with no socially evaluative cues, and reported comparable subjective and objective anxious arousal during the second and third virtual exposure, respectively. This provides a basis on which to explore further the influence of 360° VR exposure to real-life after having established effect sizes greater in magnitude on the exposure effects, in contrast to the control effects we currently obtained from our data. In addition, previous studies examining habituation effects within socially evaluative encounters typically involved multiple exposures over a prolonged time period (Finn et al., 2009; Kothgassner et al., 2021; Morina et al., 2015; Takac et al., 2019). Since our paradigm was designed with only one exposure session followed by a real-life socially evaluative task (after a 15-minute break), there is a possibility that the fear response may not be effectively inhibited.

Limitations

First, our targeted sample did not control for the confounding variables that might interact with cardiovascular responses, such as medication use, or chronic disease history (Allen et al., 2014; Linares et al., 2020). Although our manipulation groups were randomised, thus minimising the impact of this issue on group comparison findings, controlling for the aforementioned variables might help optimise the comparison of findings with the existing literature and facilitate study replication. Secondly, our in-person mental arithmetic task varied in length per participant. Although it would have been preferred to standardise the time spent, a meta-analysis on the length of the anxiogenic psychological paradigms reported that the length of an anxiogenic protocol does not explain the association between the socially evaluative stimuli and situational anxiety reactivity (Dickerson & Kemeny, 2004). However, significant differences were reported in anxious arousal stemming from the arithmetic task itself (i.e., subtracted numbers) during psychological paradigms (Goodman et al., 2017). Future research may benefit from utilising a well-established mental arithmetic task (e.g., (Kirschbaum et al., 1993)). Third, we measured objective reactivity via non-medical, consumer devices. Although Fitbit brand activity trackers have been frequently utilised as a non-invasive and continuous method of obtaining physiological data in clinical studies (Henriksen et al., 2018), these non-medical devices are not without limitations, including under and over estimation of heart rate levels (Benedetto et al., 2018), and sensitivity to movement artifacts (Thomson et al., 2019) and wear position (Salazar et al., 2017). Alternative equipment in which these issues are minimised could be considered, such as a VR compatible PPG sensor that is measured through the forehead (Gnacek et al., 2022). Lastly, we were unable to rate the actual performance of the participants. There is evidence that socially evaluative anxiogenic scenarios as opposed to the placebo variants can negatively influence elements of public speaking such as speech fluency (Buchanan et al., 2014). Measuring the performance evaluation from the participants' point of view and from an external observer point of view would provide more complete information on how performance is processed within a 360° anxiogenic psychological laboratory paradigm. In addition, we fell short of reaching our targeted sample size, resulting in a statistical power below the recommended thresholds of 80% and a lack of confidence to detect small effects of interest (based on the findings of the sensitivity analysis).

Despite limitations, this study utilised a novel technological tool which is likely to be ecologically valid to explore the anxiogenic potential of a socially evaluative virtual paradigm. Since the relevance of trait social anxiety has been discovered, further testing of our 360° virtual paradigm in clinical populations with social anxiety is warranted. Although in its early days, recent work has engaged this technology to explore social anxiety processes (e.g., avoidance or attention) (Rubin et al., 2020; Rubin et al., 2022). Our proof-of-concept findings possess informative ability to study and explore anxiety reactivity sensitively through a rigorous and standardised protocol. In addition, we reported heart rate alterations as part of the sympathetic nervous system (SNS) axis reactivity, as well as subjective anxious arousal. Cortisol responses, on the other hand, are activated by the hypothalamic-pituitary-adrenal (HPA) axis and have been widely reported in psychological anxiogenic paradigms (e.g., (Jönsson et al., 2010)) due to its sensitivity to capture anxious reactivity (Kudielka et al., 2007). Further empirical testing is required to investigate cortisol responses within our specific paradigm. Beyond utilising this paradigm in laboratories, our findings on 360° VR technology might pave the way for future work to contribute therapeutic interventions for social anxiety.

Chapter 4 – Examining Social Anxiety in Online Platforms

Abstract

Background: To date, few researchers have studied social anxiety symptoms on online social communication platforms (e.g., Skype, Zoom). The present study is an examination of self-report symptoms and cognitive processes in an online social interaction, focusing on the effect of camera (on/off) on anxiety, cognition, and mood.

Method: Participants with subclinical social anxiety gave a short impromptu talk via an online social communication platform. Participants were assigned to combinations of two between-subjects variables in which (a) dummy audience profile images and (b) the participant's web camera were manipulated (on/off). We recorded the participants' self-reported anxious arousal and explored the subjective mood, perspective taken, negative evaluative thoughts, and the post-event processing during and following the online interaction.

Results: Overall, participants reported increased anxious arousal. Furthermore, participants evaluated their performance worse and engaged in more severe negative rumination in the 'audience camera off/personal camera on' condition.

Discussion: An online videoconferencing task can induce anxious arousal in subclinical social anxiety populations. The findings are considered with reference to cognitive models of social anxiety that emphasise the role of self-focus and perspective taking in anxious arousal.

Keywords: online social platforms, social anxiety, cognitive models

Introduction

Social anxiety disorder (SAD) is characterised by the idiosyncratic cognitive biases that have influences on the prognosis of the disorder (Clark & Wells, 1995; Hofmann, 2007; Kuckertz & Amir, 2014; Moscovitch, 2009; Rapee & Heimberg, 1997; Spence & Rapee, 2016; Wong & Rapee, 2016). Clark and Wells (1995) described a cognitive model in which people with high social anxiety inwardly focus attention, becoming aware of self-referential information, which might occur in the form of physical state information, mental images and thoughts, emotions, beliefs, or memories (Ingram, 1990). In the context of social anxiety, self-focus is assumed to be activated to limit the *inaccurate* representations of the self on self-referential cognitions (e.g., 'I am boring') or on behavioural and physical expressions (e.g., shaking, blushing) that, socially anxious persons fear, might otherwise lead to negative judgments from others. Because feared consequences are deemed probable during social interactions, Clark and Wells (1995) proposed that anxious arousal is likely to be elevated, which feeds back into the internal self-focus. This cycle of the self-focus mechanism might be milder, absent, or even advantageous under low evaluative tasks and low evaluative conditions for the general population (e.g., while copying text or without the presence of an observer) (Carver & Scheier, 1981). However, enhanced internal focus is proposed to be a negative predictor of SAD (see Norton and Abbott (2016), Morrison and Heimberg (2013), and Spurr and Stopa (2002) for reviews). Compared to other models (Heimberg et al., 2010; Rapee & Heimberg, 1997), the cognitive model proposed by Clark and Wells (1995) placed less emphasis on the influence of *external social environment* (Clark, 2001; Stopa & Clark, 1993).

Rapee and Heimberg (1997) also recognised the role of self-focus in the involvement of social anxiety and have expanded upon Clark's (1995) model, with additional considerations of the external environmental cues (e.g., audience behaviour or facial expressions). This model emphasised *simultaneous* scanning of the external information as a component of social anxiety as well as monitoring salient aspects of self-image with a self-focused attention upon encountering a social situation (Schultz & Heimberg, 2008), as opposed to Clark and Wells (1995), who proposed that focusing attention inwards is associated with limited processing of external social information.

On one line of research, empirical investigations indicated that both subclinical and clinical social anxiety populations demonstrate heightened self-focused attention in social situations when compared to control groups and other anxiety disorders (Bögels & Lamers, 2002). In addition, correlational studies found evidence that self-focused attention was associated to trait social anxiety (Hutchins et al., 2021), as well as to state social anxiety (Chen et al., 2013).

Empirical research has also examined the causal link between self-focus and social anxiety utilising a variety of methods (see Bögels and Mansell (2004) for a review).

For example, Zou et al. (2007) instructed low and high blushing-anxious groups either to self-focus or task-focus while engaging in a five-minute conversation with a confederate. Self-focus instructed participants in the high blushing condition reported higher levels of social anxiety relative to task-instructed participants, while this effect disappeared among low blushing participants. Conversely, attempts to manipulate self-focused attention via the 'speech about self or other' technique often failed. For instance, Woody (1996) instructed high socially anxious participants in pairs (active or passive/listener role) to talk about their feelings, emotions (self-focus), and their pair's feelings and emotions (other focus). Enhanced self-focus increased anticipated anxiety and anxious arousal, irrespective of pairs type. In a subsequent study by Woody and Rodriguez (2000), a control group was included in the aforementioned design to explore how people with high and low social anxiety would compare under the self-focus or other focus roles. Heightened self-focus once again increased anxiety during talk, but this effect was not dependent on social anxiety levels. These two findings suggest that self-focused attention might not solely be attributed to people who are being scrutinised, or might not be specific to social anxiety. As an alternative method, for instance, Bögels et al. (2002) used self-reflecting mirrors to induce self-focused attention. During a conversation with two confederates, individuals with low and high social anxiety viewed themselves reflected in large mirrors. Although anxious arousal was not directly assessed, the self-focus manipulation failed to distinguish between low and high social anxiety on the levels of self-rated fear (visual analogue scale 0-100). Overall, these investigations concluded differently, where the discrepancies in findings might be due to the methodological variations.

External social threat in social anxiety takes the form of potential negative evaluation from others accompanied by an aberrant information processing mechanism (Morrison & Heimberg, 2013). There is evidence that people with social anxiety *attend* to the external social cues with vigilance (see Bantin et al. (2016) for a review), and also *interpret* neutral/ambiguous cues in a more negative way, relative to non-anxious individuals (Bell et al., 2011; Chen et al., 2019; Garner, Baldwin, et al., 2009; Stopa & Clark, 2000), or compared to individuals with other anxiety and mood disorders (Amin et al., 1998; Bourke et al., 2012). In addition, some computerised experimental paradigms have been utilised to explore whether these biases are *attended simultaneously* (Deiters et al., 2013; Mansell et al., 2003; Mills et al., 2014; Pineles & Mineka, 2005). These studies presented participants with pictures of their heart rhythm or connected participants to a physical tactile probe that delivers vibrations at certain intervals to enhance internal self-focus. Subjects were told that a change in the internal probe would correspond to their actual physical alterations. External visual probes took the form of superimposed letters presented within pictures of angry, happy, or neutral faces or household objects on a computer screen. The external probes also involved a headlight that was connected to an audience member while participants were giving a speech to make the paradigm more naturalistic as if it had happened during a *social interaction* (Deiters et al., 2013). Across the experiments, the effect of self-focus was present (quantified by faster reaction times), but no evidence of an interaction which involved the biased processing of external and internal information was found, perhaps supporting the social anxiety model of Clark and Wells (1995).

However, these methods have been criticised due to low ecological validity. For example, Mansell et al. (2003) and Pineles and Mineka (2005) told participants that they would be giving a speech after a computerised task in order to account for a socially evaluative context. Yet, to understand best the internal focus and the external social threat, the socially anxious person should continue to be engaged with the audience throughout the social situation as these internal and external processes occur (Schultz & Heimberg, 2008). Indeed, recent reviews have argued that the methodologies employed to operationalise these biases have a modulating effect on the relationship between social anxiety and cognitive biases (see Chen, Short, et al. (2020) and Bantin et al. (2016) for reviews).

Online social communication platforms (e.g., Zoom, Skype), on the other hand, can offer simultaneous naturalistic testing of the cognitive biases of social anxiety. That is, these social platforms often stream one's own videos during social interactions, which has the potential to enhance self-focus that would typically be missing in in-person social encounters. From the opposite perspective, another feature of online social platforms is that the image or video of others (e.g., an audience) received during a natural social interaction can be turned off, although there is still a presence of an audience, allowing for the testing of external social cues. Recent research has revealed promising findings that enhanced self-focus as a cognitive-behavioural mechanism can be activated during online video communications, for both subclinical and clinical social anxiety populations (Miller et al., 2021; Vriends et al., 2017). In addition, initial evidence exists that the negative interpretations of ambiguous external information, such as online messages (Bautista & Hope, 2015) and online social scenarios (Carruthers et al., 2019), can result in greater levels of experienced state anxiety among people high in social anxiety relative to control groups. However, the impact of the camera features in online social communication platforms, which allow the option to turn on or off speaker and audience videos/images, has not been investigated in terms of its influence on state anxious arousal and its relationship to cognitive mechanisms of social anxiety.

In the current study, we investigated how the features of online communication platforms could modulate anxious arousal during an online social interaction. We employed a public speaking protocol (McNair et al., 1982). Such stress induction protocols, where a socially evaluative threat is involved, have been shown to elicit a reliable anxious arousal response in real life (Dickerson & Kemeny, 2004; Kirschbaum et al., 1993; Osório et al., 2008), and also on online communication platforms at a population level (DuPont et al., 2022; Eagle et al., 2021; Harvie et al., 2021) as well as among people high in social anxiety (Huneke et al., 2022). Given the fact that those with high social anxiety reported less anxiety while communicating online compared to in-person social interactions (Markovitzky et al., 2012; Yen et al., 2012), and thought that online platforms were less stressful (Pierce, 2009; Prizant-Passal et al., 2016), we believe that the explorations of these online venues may thus be especially informative for the disorder and its mechanisms.

Our aim was to investigate how, over time, external social cues would interact with internal self-focus during an *online* live public speaking task in relation to subjective anxious arousal. We employed a naturalistic public speaking task where participants were asked to prepare and give a short impromptu talk on an online social communication platform. We manipulated external social cues via the absence/presence of dummy audience profile images, and internal focus (self-focus) via the absence/presence of the self-depicted video of the participants. We randomly assigned participants to the combinations of our two between-subjects variables: (a) Audience: the dummy audience profile images were displayed (camera on/off); and (b) Speaker: the participant's web camera was turned on/off. We recorded self-reported anxious arousal during key events throughout Time[9]. Additionally, we explored the subjective mood measured at pre and post during the online session. We also investigated the cognitive mechanisms of social anxiety, including retrospective ratings of the use of the observer/field perspective, negative evaluative thoughts of performance, and the post-event processing pertaining to the public speaking performance that was delivered online.

We anticipated linear increases in self-reported anxious arousal from baseline to speech task phase, which would then return to baseline during recovery (Time main effect). This prediction was based on contemporary cognitive-behavioural models of social anxiety (Clark et al., 1995; Rapee & Heimberg, 1997) and the recently developed anxiogenic online protocols (Eagle et al., 2021). Importantly, we anticipated that the generated anxious arousal would be more pronounced for those who would be exposed to their own self-depicted live video feed (Speaker manipulation) as well as the dummy audience profile images (Audience manipulation), especially just before delivering the speech during the online videoconferencing task.

[9] The number of levels for the Time factor is specified in the Results section.

Method

The data were collected between March 2021 and February 2022. Participants provided informed consent prior to the pre-screening and the videoconferencing sessions. The study was approved by the University of Southampton Research Ethics Committee (reference: 57202). Monetary compensation or research credit allocation (for students) took place upon full completion.

Participants

Participants were recruited via university-based channels (Efolio http://www.efolio.soton.ac.uk/) or through Prolific (https://www.prolific.co/) which is an online data collection platform. They all were residents of the United Kingdom and were fluent in English. The exclusion criteria were: (a) aged <18 or >55 years; (b) not having access to a properly functioning video camera or a microphone; (c) participation via mobile phones; and (d) scoring less than 15 on the Social Phobia Inventory (SPIN) (Connor et al., 2000), used to characterise a sample with subclinical to clinical social anxiety.

Three hundred and ninety-two participants were screened (253 female, aged between 18 and 55 years, M_{age}= 31.51, SD_{age}= 10.20). Among those, 133 participants (75 female, aged between 18 and 55 years, M_{age} = 32.35, SD_{age} = 10.75) were not eligible to proceed (SPIN<15, no access to a properly functioning equipment), 123 participants (85 female, aged between 18 and 52 years, M_{age} = 29.63, SD_{age} = 9.67) either did not respond to videoconferencing invitations or did not want to take part in the online session, although they were eligible (dropout rate: 47.49%). Twelve participants (eight female, aged between 18 and 50 years, M_{age} = 29.92, SD_{age} = 10.77) had technical difficulties during the online session (e.g., microphone problems), and three participants (one female, aged between 29 and 39 years, M_{age} = 32.67, SD_{age} = 5.51) were non-compliant with the videoconferencing instructions, therefore their data were not included. We compared dropout rates (n = 123) to completers (n = 121) regarding their levels of trait social anxiety (measured using the SPIN). A Welch Two Sample analysis showed no significant difference between the two groups, $t(237.46) = 0.77$, $p = .443$ $M_{diff} = 1.14$). This suggests that dropouts were occurring for various random reasons (e.g., lack of motivation, disinterest).

The final data comprised 121 participants (84 females, aged between 18 and 54 years (M_{age} = 32.61, SD_{age} = 9.99). We employed a complete factorial design: that is, the eligible participants were randomly assigned to a combination of two conditions, in which (a) the dummy audience profile pictures (Audience) and (b) the participant video camera (Speaker) was set to either *on* or *off* during the online session.

Power analysis

We determined the sample size using the R package 'WebPower'[10] (Zhang et al., 2018) for a three-way interaction effect on subjective anxious arousal. We estimated a medium effect size (Cohen's f = .39) that is commonly observed in social evaluative performance tasks where an audience is present (Cohen's d CIs= ..50, .84) (Dickerson & Kemeny, 2004). Additionally, previous *online-administered* paradigms for subclinical social anxiety populations have reported medium to large effect sizes (Harvie et al., 2021; Vriends et al., 2017). We chose to stay within this range in terms of effect sizes, as no one had reported such a design before with manipulation of both internal and external social cues within an online socially evaluative encounter. To have .80 power at $p < .05$, the *a priori* targeted sample size was 116, which we exceeded (N = 121).

Materials

Dummy Audience

The audience consisted of 20 attendees who were essentially dummy accounts that a second experimenter logged into on other devices/browser windows and set to mute**.** See Figure 21 for an example interface of the online videoconferencing session. To bolster a socially evaluative context, we set dummy audience profile images using real people's social media profile photos (with their consent having been obtained beforehand). The images were presumed to be neutral in facial expressions and equal in gender[11]. Each profile image was given a corresponding name, and each dummy audience member entered the videoconferencing session in a fixed order.

Measures

Screening

Participants completed the SPIN (Connor et al., 2000) to characterise a sub-clinical/clinical sample. The SPIN consists of 17 items that assesses the spectrum of SAD on the dimensions of fear (e.g., of being criticised), avoidance (e.g., of making speeches), and physiological unpleasantness (e.g., heart palpitations). It is rated on a five-point Likert-type scale (0 = not at all, 4 = extremely). Its use as a screening tool for SAD has been validated and has excellent psychometric properties (α_{total} = .95; 88.6% of participants with SAD were correctly distinguished (Antony et al., 2006)). A threshold

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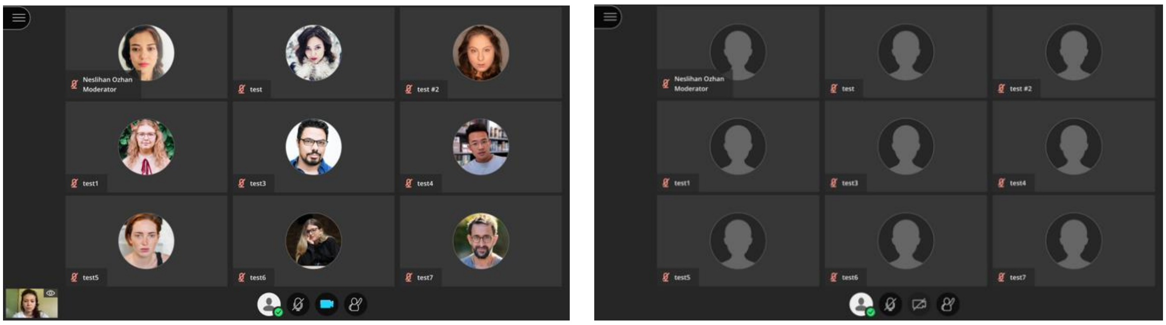
[10] We used WebPower for power analysis calculation since G*Power cannot properly handle power effects for three-way interactions.

[11] Only the moderator had their videos accessible along with dummy audience profile images when the Audience condition was on. The moderator kept a neutral facial expression throughout the social interaction.

Figure 21

Example Screenshots from the Online Videoconferencing Session



Note. Left figure depicts when dummy audience images (Audience) and participant video (Speaker) are on. Right figure depicts when audience images (Audience) and participant video (Speaker) are off.

score of 15 can distinguish between those with varying severity of social anxiety and those who do not exhibit any signs of social anxiety (Connor et al., 2000).

Baseline Measures

Participants completed the following measures to allow for baseline between-subjects comparisons: GAD-7 (Spitzer et al., 2006) to assess anxiety symptom severity; Patient Health Questionnaire, PHQ-9 (Kroenke & Spitzer, 2002), to assess depressive symptoms; Personal Report of Communication Apprehension - public speaking sub scale, PRCA-24 (McCroskey, 2015), to measure communication apprehension levels when performing in public; and the Revisited Green Paranoid Thoughts Scale - Persecutory Paranoia Subscale, R-GPTS; (Freeman et al., 2019), to explore paranoia levels. All these measures showed good psychometric properties (alphas > .87) for GAD-7, PHQ-9, PRCA-24, R-GPTS-PP (Beard et al., 2016; Freeman et al., 2019; Löwe et al., 2008; McCroskey et al., 1985).

Primary Outcome Measures

GAD-7$_{Modified}$

Participants completed GAD-7$_{Modified}$, a version of the seven-item GAD-7 (Spitzer et al., 2006), to measure state anxiety severity. Participants rated their level of anxiety in their response to the question, ‘How often have you been bothered by the following *right now*?’ on several aspects of anxious arousal (e.g., ‘trouble relaxing’) on a *modified* scale ranging from 0 (not at all) to 4 (extremely). We only administered four out of seven GAD-7 items to be able to capture the level of anxious arousal immediately in between speech preparation and delivery in the online videoconferencing session (See Appendix C for the modified version). GAD-7 can detect social anxiety symptoms with .88 sensitivity (95% CI

= .77 - .95) (Kroenke et al., 2007). The four-item GAD-7$_{Modified}$ for our sample at the baseline showed good α of .89 (95% CI = .84 - .92, bootstrapped based on 1000 samples)

Subjective Units of Distress (SUDS)

Participants rated their state of anxiety intensity in response to the question, 'How anxious do you feel right now?' on a visual analogue scale, ranging from 0 being 'not at all' to 100 being 'extremely anxious' (Wolpe, 1990).

Social Anxiety Session Change Index (SASCI$_{Modified}$)

Participants rated their state social anxiety using the Social Anxiety Session Change Index (SASCI) (Hayes et al., 2008). SASCI is a four-item instrument that has been developed to monitor therapy progress for clinicians and rated on a seven-point Likert-type scale, ranging from 1 (much less than at the start of treatment) to 4 (not different from at the start of treatment) to 7 (much more than at the start of treatment). We modified the items (e.g., 'How concerned are you that others are thinking badly of you?') as well as the scoring range (0 = not at all, 4 = extremely). Across therapy sessions, SASCI showed good to excellent psychometric properties (α = .84 - .94) (Hayes et al., 2008). In our sample, the SASCI$_{Modified}$ at baseline showed an α of .85 (95% CI = .80 - .89, bootstrapped based on 1000 samples). See Appendix C for the modified version.

Exploratory Outcome Measures

Positive and Negative Affect

Participants recorded their self-reported negative and positive mood via the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988). PANAS consists of two 10-item subscales that correspond to positive mood (e.g., interested) and negative mood (e.g., distressed), rated on a five-point scale (1 = 'very slightly or not at all', 5 = 'extremely'). Both subscales demonstrated excellent psychometric properties ($\alpha_{\text{positive affect}}$ =.89, $\alpha_{\text{negative affect}}$ =.85 (Crawford & Henry, 2004).

Performance Evaluations

Speech Performance Scale, SPS, (Rapee & Lim, 1992) is a 17-item instrument with some reverse coded items (e.g., 'I had a clear voice', 'I was blushing'), and is rated on a scale ranging from 0 (not at all) to 4 (very much). Higher scores account for better performance evaluation. Participants completed this measure twice: the first administration was based on their performance from their point of view (self, how you felt you actually performed), and the second administration was based on others' points of view (observer, how you think others felt when you performed), regarding their performance. As an additional outcome variable, the mean difference between self and others' perspective on the performance evaluations of participants was computed for analysis as a measure of discrepancy. In addition, I (first author) and a second experimenter, who helped in the online session with a dummy audience set up, rated the performance of participants. The intraclass correlation coefficient (ICC) was estimated to measure the strength of inter-rater agreement, which is a widely used and established means of determining measurement agreement (Koo & Li, 2016). A two-way mixed effects model that was specified on the data (N=90)[12] revealed good agreement between the assessors (ICC=.73, $F(89) = 3.70$, $p <.001$ CI%95 [.58 -.82]). We therefore only included the scores from the first experimenter on the complete data (N=121) as an outcome measure of assessor rating. To note, some questionnaire items for this particular analysis were excluded[13] due to not being applicable to our group conditions (e.g., blushing ratings when Speaker video was turned off).

Post-event Processing

The Thoughts Questionnaire (TQ) consists of 29 items (three sub scales, 11 negative ruminations, e.g., ‘I must have looked stupid’; 16 positive ruminations, e.g., ‘My speech was good’; and two general ruminations, e.g., the situation overall), which are rated on a scale ranging from 0 (never) to 4 (very often). Higher scores indicate more persistent post-event processing (negative, positive, or general). We used the negative rumination subscales for the analysis. The TQ showed excellent psychometric properties across subscales (α = .79 -. 94) (Edwards et al., 2003).

Observer & Field Perspective

Participants rated the degree of their perspective related to their online public speaking performance task on a seven-point scale ranging from -3 (entirely looked through my eyes) to +3 (entirely observed myself from an external point of view), consistent with the administration in the literature (Hackmann et al., 1998; Wells et al., 1998; Wells & Papageorgiou, 1998). We provided simple written descriptions of the ‘observer’ and ‘field’ perspective for the participants prior to their ratings.

Experimental Protocol

The videoconferencing session took place on Blackboard Collaborate (https://ca.bbcollab.com/). Participants who scored higher than 15 on the SPIN (Connor et al., 2000) with a properly functioning web camera on a desktop were invited to an online videoconferencing session. Figure 22 depicts the experimental protocol. The script for the online social interaction can be found in Appendix F for the conditions where participants had their video enabled. The videoconferencing session had several phases that were performed in a fixed order:

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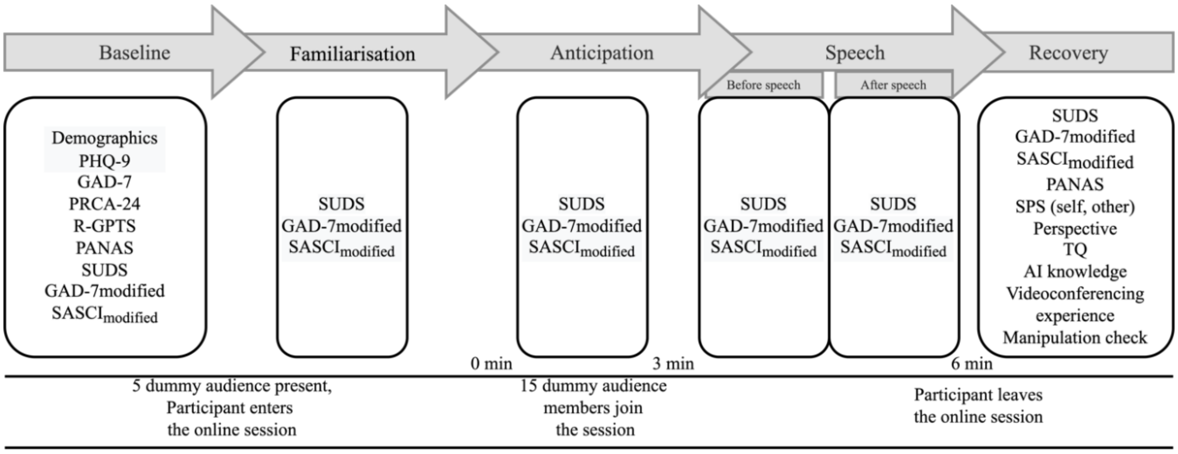
[12] 25.62% of the data for second experimenter ratings was missing, therefore we estimated the Intraclass Correlation Coefficient (ICC) after dropping the missing cases (Listwise deletion).

[13] Item numbers 2, 9, 10, and 11 out of 17 items are excluded.

Figure 22

A Visualised Depiction of the Experimental Protocol



Note. PHQ -9 (Patient Health Questionnaire-9), GAD-7 (Generalised Anxiety Disorder Assessment), PRCA-24 (The Personal Report of Communication Apprehension), R-GPTS (The Revised Green et al. Paranoid Thoughts Scale), PANAS (The Positive and Negative Affect Schedule), SUDS (Subjective Units of Distress Scale), SASCI (Social Anxiety Session Change Index), SPS (Speech Performance Scale), TQ (Thoughts Questionnaire), AI (Artificial Intelligence).

Baseline: Before joining the online videoconferencing session, participants recorded their demographic information, levels of trait/state anxiety, communication apprehension, paranoia, and mood, in an online survey using the software Qualtrics XM (https://www.qualtrics.com/) (Qualtrics, 2021).

Familiarisation*:* Upon completion of the Baseline phase, the participants were automatically directed to the online videoconferencing session. Five dummy audience members were already present either with or without profile images, depending on their experimental group allocation. Once participants joined the online session, the moderator welcomed them and introduced the online videoconferencing environment. We restricted the video camera access in advance for those who were assigned to the no live video feed level of the Speaker condition, and elsewise we requested participants to keep their web camera turned on throughout the online session. At the end of this phase, we recorded participants' self-reported state anxiety levels (GAD-7$_{Modified}$, SUDS, and SASCI$_{Modified}$), in which they posted their answers to a private chat.

Anticipation*:* Then, participants prepared a three-minute talk on a particular topic (i.e., 'The Future of Artificial Intelligence: The Harms and Benefits', and the prompts 'dependency on machines', 'restricted work', 'unemployment', 'less room for errors', and

'AI in risky situations'). After one and a half minutes of preparation, we recorded their state anxiety levels (GAD-7*Modified*, SUDS, and SASCI*Modified*). Upon questionnaire completion (the last one and a half minutes of their preparation), 15 more dummy audience members entered the session, totalling 20 dummy audience members present in the session (except the moderator and the participant).

***Speech**:* Once the preparation time was over, the moderator introduced the participant to the dummy audience as today's speaker. Two dummy audience members interacted in the session by posting 'Hi everyone; Hello!' in the chat. Then, the participants were verbally instructed to deliver their rehearsed speech for the next three minutes. Before their speech, their state anxiety levels (GAD-7*Modified*, SUDS, and SASCI*Modified*) were recorded. After the speech, 15 of the 20 dummy audience members left the online session, with two dummy audience members interacting in the chat by posting 'Thank you!, Thanks, bye everyone' before leaving. Then, the participants' state anxiety levels (GAD-7*Modified*, SUDS, and SASCI*Modified*) were recorded once again, using the private chat.

***Recovery**:* Before leaving the online session, participants were sent a final web link to complete additional post-activity measures to record their state anxiety, mood, retrospective performance evaluations, perspective taken, and post-event processing (GAD-7*Modified*, SUDS, and SASCI*Modified*, PANAS, SPS, observer/field perspective, TQ) in Qualtrics. Participants also recorded their awareness of the audience and their self-depicting video (-3 not aware at all, 0 = neutral, +3 totally aware) as a manipulation check, their videoconferencing experience (0 = not at all, 10 = extreme), and AI knowledge (0 = not at all, 4 = a great deal). The videoconferencing session was terminated after sending the final questionnaire link.

During the preparation phase, a countdown timer was available which was set to three minutes. During the speech phase, whilst approaching the end of their three-minute talk, the moderator sent two private chat messages (i.e., last 30 seconds, last ten seconds) to make participants aware of the time they had remaining. Participants' self-report ratings during the online session were only visible to the moderator, and this was made clear to the participants. Participants were instructed not to use any other materials or view other monitor screens during their talk. We also videotaped the online session, as previous research observed greater anxious reactivity when combinations of social-evaluative factors (e.g., audience and videotape) were present as opposed to when just one was present (Dickerson & Kemeny, 2004).

Data Analytic Strategy

All statistical analyses were performed using R Software, version 4.2.0. (R Core Team, 2022). Demographic differences were analysed using one-way Analysis of Variances (ANOVAs). We used the package 'afex' (Singmann et al., 2022) to run our omnibus linear mixed-effects models. We assessed the change in self-reported anxiety

(GAD-7$_{Modified}$, SUDS, and SASCI$_{Modified}$) and affect (PANAS) through Time on Speaker*Audience interaction. To explore the two-way Speaker*Audience interaction effects on performance evaluations, post-event processing, and perspective taking, we conducted separate between-subjects models. We used the package ‘emmeans’ (Lenth et al., 2018) to carry out simple effect analyses where there was a significant two-way interaction and to carry out post-hoc tests with customised contrasts where there was a significant main effect of Time. Post-hoc tests were adjusted using the Bonferroni correction.

For analyses where there was a lack of sphericity in our repeated-measures, Greenhouse-Geisser corrections were used. Before primary models were performed, Q-Q plots showed slight non-normalities on some primary outcome measures (i.e., SASCI$_{Modified}$). No extreme outliers were detected. In addition, sample size was unequal between the groups. Despite being robust against slight departures from non-normality, unbalanced designs can inflate the Type I error for *F* tests (Rusticus & Lovato, 2014). Therefore, we verified our analyses using Welch-James test statistics. We re-analysed our data on 20% trimmed means and bootstrapped sample (N = 1000) with winsorised variances using the package ‘welchADF’ (Villacorta, 2017). Supplementary analysis is provided in Appendix G where lack of convergence is observed between test results.

Results

Group Characteristics

One-way ANOVAs, using Welch’s *F* as the test statistic, confirmed that the groups did not differ in terms of gender, age, and self-report baseline measures including trait anxiety, social anxiety, and paranoia (see Table 14). Participants across four groups reported moderate levels of videoconferencing experience. The mean score of SPIN ranged from 28.55 ± 9.28 to 33.88 ± 12.04 across four groups, indicating mild to moderate social anxiety symptoms for our sample.

Manipulation Checks

We conducted separate Analysis of Covariances (ANCOVAs) on two manipulation checks for the Audience and Speaker variables. We controlled for Audience factor while testing the Speaker manipulation due to our complete factorial design, or vice versa. Speaker manipulation, $F(1, 118) = 3.86$, $p = .052$, η2p = .032 showed a trend whereas Audience manipulation, $F(1, 118) = 2.41$, $p = .123$, η2p = .020, did not yield significance. These findings might raise concerns about the effectiveness of our camera manipulation. That is, participants' awareness of their own videos, whether they were switched on or off, and participants’ awareness of the audience in the online videoconferencing session, whether participants saw the audience's profile images or not, was comparable.

Table 14

Baseline Group Characteristics

	Analysis Sample (*N* = 121)								
	Audience ON, Speaker (Video) ON n = 29		Audience ON, Speaker (Video) OFF n = 29		Audience OFF, Speaker (Video) ON n = 32		Audience OFF, Speaker (Video) OFF n = 31		
Variable	M	*SD*	M	*SD*	M	*SD*	M	*SD*	Test
Age	30.28	9.52	35.10	10.28	30.28	9.54	34.87	9.99	Welch's *F* (3, 64.69) = 2.26, *p* = .089
PHQ-9	7.38	5.71	7.07	5.08	7.31	5.91	8.65	7.04	Welch's *F* (3, 64.78) = 0.35, *p* = .789
SPIN	30.45	12.04	28.72	10.21	33.88	10.62	28.55	9.28	Welch's *F* (3, 64.36) = 1.77, *p* = .161
GAD-7	11.41	8.24	11.48	6.31	12.09	7.21	10.77	6.83	Welch's *F* (3, 64.54) = 0.18, *p* = .907
PRCA-24	22.07	4.80	22.97	3.65	22.01	4.93	21.16	3.63	Welch's *F* (3, 64.37) = 1.20, *p* = .316
R-GPTS	3.90	6.61	4.39	7.33	7.19	7.36	4.55	5.82	Welch's *F* (3, 64.45) = 1.26, *p* = .296
Videoconferencing Experience (0-10)	5.72	2.45	6.07	2.49	5.62	2.14	5.45	2.03	Welch's *F* (3, 64.18) = 0.37, *p* = .776
AI Knowledge (0-4)	1.01	0.80	1.07	0.65	1.34	0.91	1.39	1.09	Welch's *F* (3, 64.47) = 1.44, *p* = .240
	n	%	n	%	n	%	n	%	
Gender (Female)	24	83	23	79	17	53	20	65	$\chi 2$ = 12.07, *p* >.005
Ethnicity (White)	21	72	23	79	20	62	22	71	$\chi 2$ = 11.34, *p* >0.10

Note. PHQ -9 (Patient Health Questionnaire-9), SPIN (The Social Phobia Inventory), GAD-7 (Generalised Anxiety Disorder Assessment), PRCA-24 (The Personal Report of Communication Apprehension), R-GPTS (The Revised Green et al. Paranoid Thoughts Scale), AI (Artificial Intelligence). For PRCA-24 and R-GPTS the subscales of Public Speaking and Persecutory Paranoia were used, respectively. Degrees of freedom (df) were adjusted for not assuming equal variances among between-subjects groups.

Main Analyses: State Anxiety and State Social Anxiety

Table 15 lists the interaction and main effects as well as follow-up tests on state anxiety measures of GAD-$7_{Modified}$, SUDS, and $SASCI_{Modified}$. All observed means and standard deviations for outcome measures are presented in Table 16.

Separate 2 (Speaker: on, off) x 2 (Audience: on, off) x 6 (Time: baseline, familiarisation, anticipation, before speech, after speech, recovery) linear mixed-effects models were run with GAD-$7_{Modified}$ [14], SUDS, and $SASCI_{Modified}$ as dependent variables[15]. The three-way interactions were not significant for any of the outcome variables (*p*s>.181). This finding does not support our main hypothesis, suggesting that the experienced anxious arousal throughout the online session is not dependent on camera manipulation combinations. The main effect of Speaker condition was significant for SUDS, $F(1, 117) = 4.10$, $p = .045$, η2p = .034, suggesting that, in general, participants felt more anxious when their video camera was on ($M = 55.91$, $SD = 27.41$) than those who did not receive any self-video information ($M = 47.46$, $SD = 28.76$). There was a significant main effect of Time for GAD-$7_{Modified}$, $F(2.93, 342.93) = 41.55$, $p <.001$, η2p = .262, for SUDS, $F(2.56, 300.05) = 48.80$, $p <.001$, η2p = .294, and for $SASCI_{Modified}$, $F(3.04, 355.91) = 30.57$, $p <.001$, η2p = .207. Follow-up analyses with customised contrasts (consecutive) revealed that state anxiety and state social anxiety significantly increased following the Baseline period, peaked just before delivering the speech, and then decreased till Recovery for state anxiety (GAD-$7_{Modified}$ and SUDS). The pattern was similar for state social anxiety ($SASCI_{Modified}$), except that participants' social anxiety increased as they left the online session (After speech versus Recovery) $p <.001$). In addition, the only nonsignificant contrast among Time pairs was that participants' state anxiety ratings on SUDS measurement during Anticipation were comparable to those ratings when they first joined the session (Familiarisation), $p = .478$ (see Table 15 for test statistics and Table 17 for observed means for Time main effect). Overall, these findings indicate that even though a stressful online videoconferencing task was efficient in evoking anxiety among socially anxious individuals, the camera features of the online social platforms did not add up differently to the level of anxious arousal that was generated. Additionally, once the online session was ended, participants' levels of state anxiety (SUDS) reduced while their levels of social anxiety ($SASCI_{Modified}$) increased. See Figure 23 for the interaction plots for GAD-$7_{Modified}$, SUDS and $SASCI_{Modified}$..

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[14] The 'Recovery' time point 'after online session' is not included in the GAD-$7_{Modified}$ main analysis due to questionnaire instruction retrospectively reflecting on the online task ('How often have you been bothered by the following *during the online session*?') instead of reflecting on the state levels ('How often have you been bothered by the following *right now*?').

[15] We re-ran the analyses on each outcome variable while controlling for trait measures, gender, AI knowledge or videoconferencing experience. The results yielded the same findings.

Table 15

Test Statistics of Omnibus and Follow-up Tests on the Self-Reported Anxious Arousal Throughout the Online Session

	State Anxiety / GAD-7$_{Modified}$			State anxiety / SUDS			State Social Anxiety / SASCI$_{Modified}$		
	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p	(df), *F*	*p*	η2p
Speaker	(1, 117), 0.93	.336	.008	(1, 117), 4.10	**.045**	.034	(1,117), 2.79	.097	.023
Audience	(1, 117), 0.064	.800	.001	(1, 117), 0.02	.894	<.001	(1, 117), 0.12	.732	.001
Time	(2.93, 342.93), 41.55	**<.001**	.262	(2.56, 300.05), 48.80	**<.001**	.294	(3.04, 355.91), 30.57	**<.001**	.207
Audience X Time	(2.93, 342.93), 0.11	.951	.001	(2.56, 300.05), 0.27	.816	.002	(3.04, 355.91), 0.97	.408	.008
Speaker X Time	(2.93, 342.93), 1.40	.234	.012	(2.56, 300.05), 1.37	.256	.012	(3.04, 355.91), 1.65	.177	.014
Audience X Speaker	(1, 117), 0.40	.530	.003	(1, 117), 0.12	.727	.001	(1, 117), 1.36	.247	.011
Audience X Speaker X Time	(2.93, 342.93), .039	.757	.003	(2.56, 300.05), 0.51	.648	.004	(3.04, 355.91), 1.63	.181	.014

Change in Time	*t*(116)	Lower Upper 95% CI	*p*	*d*	*t*(116)	Lower Upper 95% CI	*p*	*d*	*t*(116)	Lower Upper 95% CI	*p*	*d*
Baseline to Familiarisation	6.48	[1.02 2.33]	**<.001**	0.45	6.28	[5.18 12.56]	**<.001**	0.36	4.06	[0.45, 2.10]	**<.001**	0.32
Familiarisation to Anticipation	3.59	[0.26 1.50]	**.002**	0.23	1.68	[-1.28 5.84]	.478	0.08	5.73	[0.58, 1.57]	**<.001**	0.24
Anticipation to Before Speech	4.58	[0.50 1.74]	**<.001**	0.25	6.47	[5.42 12.77]	**<.001**	0.40	4.92	[0.41, 1.36]	**<.001**	0.19
Before Speech to After Speech	-8.87	[-3.75 -2.08]	**<.001**	0.65	-9.98	[-29.14 -17.03]	**<.001**	0.81	-8.89	[-3.54, -1.93]	**<.001**	0.54
After Speech to Recovery	-	-	-	-	-3.46	[-5.93 -0.82]	**.003**	0.11	4.49	[0.32, 1.23]	**<.001**	0.15

Note. GAD-7 (Generalised Anxiety Disorder Assessment), SUDS (Subjective Units of Distress), SASCI (Social Anxiety Session Change Index). See Figure 22 for a summary of the protocol and time points. Effect size of partial eta squared (η2p) is reported for main effects and interactions, and d (M_2 – M_1)/SD_{pooled} is reported for pairwise comparisons.

Table 16

Observed Means and Standard Deviations for Audience (on/off) and Participant (on/off) Groups Across Time for the Outcome Measures

	Audience ON / Speaker ON n = 29						Audience ON/ Speaker OFF n = 29						Audience OFF/ Speaker ON n = 32						Audience OFF/ Speaker OFF n = 31					
Measure	T1 M(SD)	T2 M(SD)	T3 M(SD)	T4 M(SD)	T5 M(SD)	T6 M(SD)	T1 M(SD)	T2 M(SD)	T3 M(SD)	T4 M(SD)	T5 M(SD)	T6 M(SD)	T1 M(SD)	T2 M(SD)	T3 M(SD)	T4 M(SD)	T5 M(SD)	T6 M(SD)	T1 M(SD)	T2 M(SD)	T3 M(SD)	T4 M(SD)	T5 M(SD)	T6 M(SD)
GAD-7$_{Modified}$	4.00 (4.64)	6.17 (3.16)	6.69 (3.96)	8.07 (4.27)	5.28 (4.42)	8.00 (4.44)	4.21 (3.43)	5.62 (3.68)	7.00 (4.71)	7.59 (4.61)	4.72 (4.47)	7.93 (4.93)	4.31 (3.47)	5.97 (3.58)	6.81 (4.17)	8.53 (4.56)	5.78 (4.68)	8.75 (4.40)	3.97 (3.95)	5.42 (3.57)	6.19 (4.20)	7.00 (4.65)	3.74 (4.14)	6.42 (4.38)
SUDS	46.28 (25.11)	58.93 (21.40)	62.76 (22.62)	72.41 (21.24)	48.35 (30.14)	43.93 (31.33)	44.86 (27.16)	52.14 (28.66)	54.14 (25.30)	63.62 (29.36)	39.17 (30.98)	37.05 (32.16)	49.62 (20.4)	58.59 (24.37)	60.41 (28.03)	70.37 (27.35)	50.62 (29.56)	48.41 (30.18)	45.18 (24.7)	51.77 (24.64)	53.26 (27.35)	60.55 (30.10)	36.48 (25.01)	31.72 (23.18)
SASCI$_{Modified}$	5.69 (4.72)	7.21 (4.18)	8.52 (4.84)	9.24 (4.77)	6.59 (5.57)	6.38 (5.45)	5.69 (4.12)	6.48 (4.08)	7.83 (4.65)	8.69 (5.00)	6.00 (5.26)	6.69 (4.99)	5.47 (3.10)	7.69 (4.18)	8.62 (4.77)	9.62 (4.97)	7.16 (4.93)	8.69 (4.73)	5.19 (3.72)	5.77 (3.58)	6.48 (4.02)	7.45 (4.60)	4.35 (4.43)	5.45 (4.81)
PANAS (PA)	23.10 (8.50)	-	-	-	-	23.45 (9.59)	25.34 (6.96)	-	-	-	-	26.48 (6.84)	25.65 (6.79)	-	-	-	-	25.03 (8.25)	27.39 (8.01)	-	-	-	-	28.32 (10.13)
PANAS (NA)	15.59 (6.68)	-	-	-	-	16.69 (6.69)	15.76 (4.45)	-	-	-	-	16.97 (6.39)	17.81 (4.75)	-	-	-	-	19.88 (6.66)	17.16 (5.65)	-	-	-	-	15.48 (5.65)

After videoconferencing (T6)	Audience ON / Speaker ON	Audience ON/ Speaker OFF	Audience OFF/ Speaker ON	Audience OFF/ Speaker OFF
Performance (Self Ratings)	35.41 (11.95)	35.59 (13.12)	30.19 (14.31)	41.13 (10.08)
Performance (Other Perspective)	36.17 (11.29)	35.38 (11.96)	30.72 (14.57)	40.42 (9.75)
Performance (Experimenter Ratings)	35.4 (12.01)	35.61 (13.23)	30.20 (14.31)	41.10 (10.1)
Observer/Field Perspective	-0.76 (2.12)	-1.00 (1.67)	-0.19 (1.69)	-0.81 (1.68)
Post-event processing (Negative)	26.21 (14.94)	29.07 (13.86)	33.31 (15.47)	24.87 (12.62)

Note. GAD-7 (Generalised Anxiety Disorder Assessment), SUDS (Subjective Units of Distress), SASCI (Social Anxiety Session Change Index). T1= Baseline, T2 = Familiarisation, T3 = Anticipation, T4 = Before Speech, T5 = After Speech, T6 = Recovery. GAD-7$_{Modified}$ includes four of the original seven items. T6 for GAD-7$_{Modified}$ instructions targeted the peak effects of self-reported anxiety during the videoconferencing task. For PANAS, higher scores represent more negative and positive affect. PA = positive affect, NA = negative affect. For Performance, low scores denote worse performance evaluations. Perspective was measured on a scale ranging from -3 (field perspective) to +3 (observer perspective). For Post-event Processing, the lower scores denote less severe ruminations.

Table 17

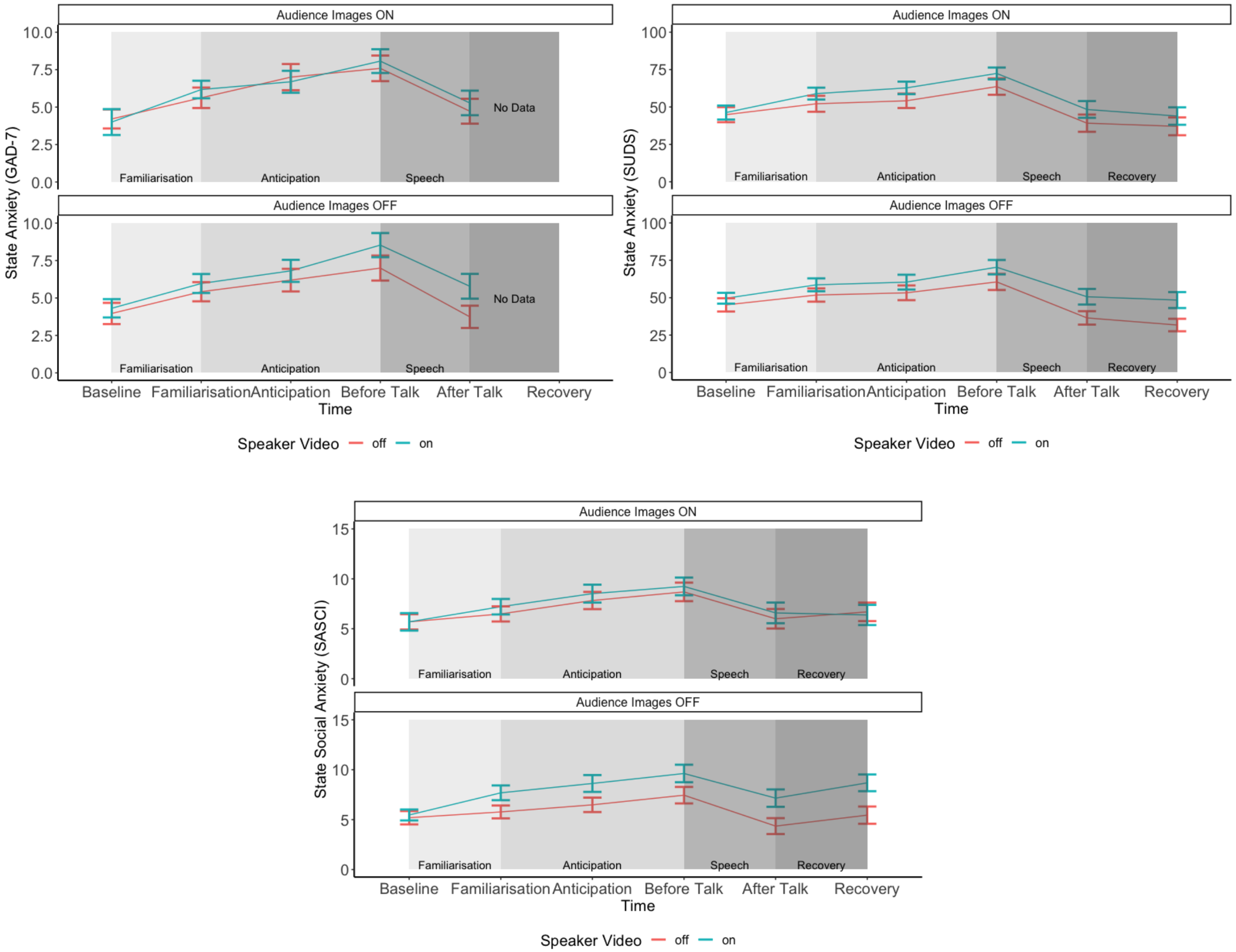
Observed Means and Standard Deviations Across Time for State Anxiety Measures

	Time					
	Baseline	Familiarisation	Anticipation	Before speech	After speech	Recovery
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
GAD-$7_{Modified}$	4.12 (3.86)	5.79 (3.47)	6.67 (4.22)	7.80 (4.51)	4.88 (4.45)	7.78 (4.56)
SUDS	46.54 (24.15)	55.38 (24.81)	57.64 (26.14)	66.73 (27.38)	43.71 (29.23)	40.34 (29.70)
$SASCI_{Modified}$	5.50 (3.89)	6.79 (4.03)	7.86 (4.60)	8.75 (4.85)	6.02 (5.10)	6.82 (5.07)

Note. GAD-7 (Generalised Anxiety Disorder Assessment), SUDS (Subjective Units of Distress), SASCI (Social Anxiety Session Change Index). GAD-$7_{Modified}$ includes four of the original seven items. ‘Recovery’ for GAD-$7_{Modified}$ instructions targeted the peak effects of self-reported anxiety during the videoconferencing task.

Figure 23

*Three-way Speaker*Audience*Time Interaction Plots for State Anxiety and State Social Anxiety*



Our data revealed non-normal distributions of residuals on the $SASCI_{Modified}$ measure. We re-ran the analysis using Welch-James statistics (Villacorta, 2017). The findings revealed a discrepancy in the $SASCI_{Modified}$, which has been documented in Appendix G.

Positive and Negative Affect

Separate 2 (Speaker: on, off) x 2 (Audience: on, off) x 2 (Time: pre online session, post online session) linear mixed-effects models were run with PANAS positive affect and negative affect as dependent variables. Only a significant main effect of Speaker was found for positive affect, $F(1, 395.2) = 5.85$, $p = .0163$. No other significant main effects or interaction were found on positive affect (Fs < 3.59, ps>.069) or negative affect (Fs < 3.11, ps>.073).

Performance Evaluations

From 'Self' Perspective

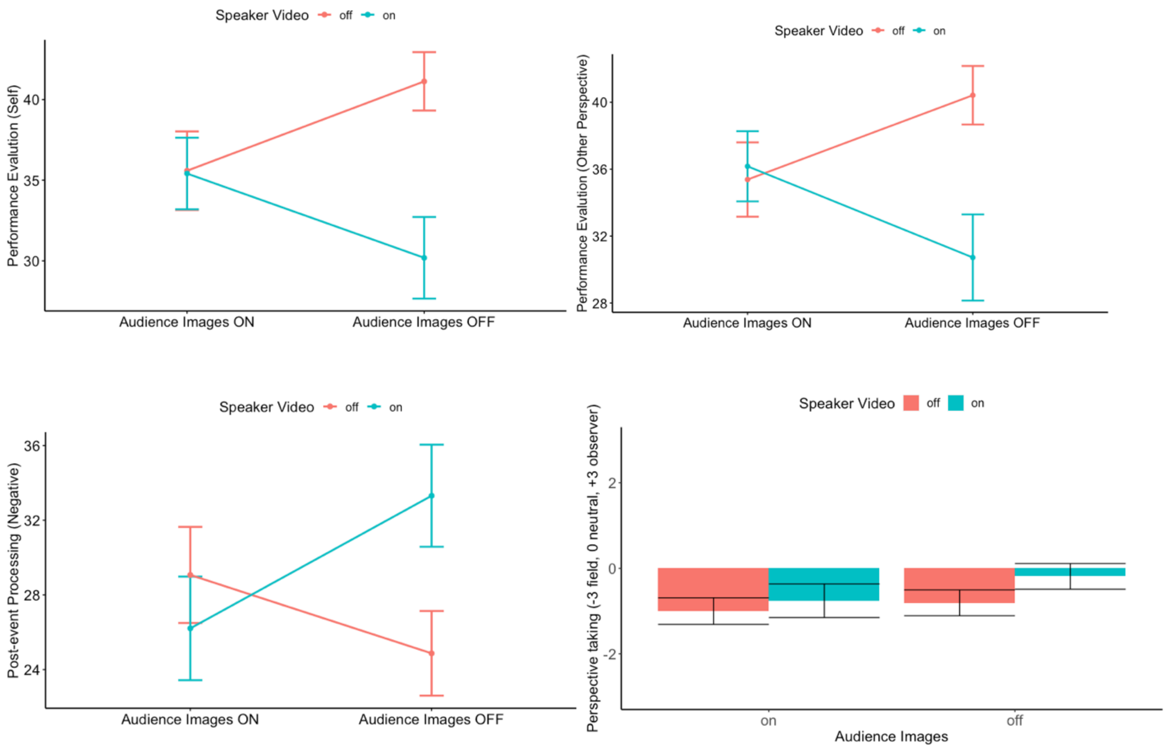
The main effect of Speaker was significant, meaning that not having access to video feedback for participants during the online session resulted in more negative performance evaluations, $F(1,117) = 5.99$, $p = .016$, ηp2 = . 049. A main effect of Speaker, $F(1, 117) = 0.01$, $p = .945$, ηp2 < .001, was subsumed in significant interaction between Audience and Speaker, $F(1, 117) = 5.62$, $p = .019$, ηp2 = .046. As characterised in Figure 24 (top left panel), a simple effects analysis confirmed that when dummy audience profile images were on, participants' performance evaluations were comparable on the levels of their self-depicted videos (on/off), $F(1,117) = .003$, $p = .958$, ηp2 < .001, $M_{diff} = 0.172$, SE = 3.28. However, when participants did not have access to the profile pictures of the dummy audience, performance evaluations were significantly worse when the participants' video was on relative to when it was off, $F(1,117) = 12.11$, $p < .001$, ηp2 = .094, $M_{diff} = 10.55$, SE = 3.14).

From 'Others' Perspective

Using 'other/observer' perspective revealed identical patterns to 'self' when evaluating performance. There was no main effect of Audience, $F(1,117) = 0.01$, $p = .925$, ηp2 < .001, while the main effect of Speaker was marginally significant, $F(1, 117) = 4.12$, $p = .045$, ηp2 = .034. The interaction of Audience* Speaker was significant, $F(1, 117) = 5.72$, p = .018, ηp2 = .047. As can be seen in Figure 24 (top right panel), a simple effects analysis suggested that performance evaluations from others' perspectives of the participants were comparable on the levels of self-depicted video availability (on/off) if the dummy audience profile images were available, $F(1, 117) = 0.063$, $p = .803$, ηp2 = .001, $M_{diff} = 0.79$, SE = 3.17). However, when there were no profile images available for the dummy audience, participants' performance evaluation from others' perspective was

Figure 24

*Performance Evaluations from 'Self' and 'Other' Perspectives, Perspective Taken, and Post-event Processing for Speaker*Audience Interaction*



Note. The lower scores denote worse performance evaluations and less severe post-event processing. Error bars represent the standard error (SE).

significantly worse when their video was on relative to when it was off, $F(1, 117) = 10.19$, $p = .002$, ηp2 = .080, $M_{diff} = 9.70$, SE = 3.04).

Discrepancy between 'Self' and 'Observer'

No main effects or the interaction effect was significant (Fs < 1.10, ps>.297), meaning that the combination of Audience and Speaker manipulations did not quantify a significant discrepancy on how performance evaluations were rated, whether participants recalled their performance from the 'Self' and 'Observer' perspectives.

Experimenter Ratings

None of the effects were significant (Fs < 2.04, ps>.156), meaning that participants performed similarly based on external observer ratings under various camera conditions (on/off).

Observer versus Field Perspective

No main effects or the interaction effect was significant (Fs < 1.73, ps>.190), suggesting that participants did not employ a particular perspective during the online session based on their group allocation. A visual pattern Figure 24, bottom right panel) showed that participants in any combinations of Speaker*Audience manipulation tended to employ the 'Field' perspective during the online session, although participants who had their self-depicting video on when there were no available audience profile images were closer to switching to the 'Observer' perspective in terms of numerical representations, but this effect was not significantly meaningful.

Post-event Processing

The main effect of Audience was not significant on negative post-event processing, $F(1, 117) = 0.313$, $p = .577$, ηp2 = .003, as well as the main effect of Speaker $F(1, 117) = 1.15$, $p = .285$, ηp2 = .010. However, the interaction effect of Audience and Speaker was significant, $F(1, 117) = 4.74$, $p = .032$, ηp2 = .039. As evident in Figure 24 (bottom left panel), simple effects analysis confirmed that in the presence of Audience profile image information, the negative ruminations of participants with their self-depicted video being on or off were comparable, $F(1, 117) = 0.58$, $p = .447$, ηp2 = .005, $M_{diff} = 2.86$, SE = 3.74. However, when there was no available Audience image information, participants ruminated more negatively when their videos were on relative to when they were off, $F(1, 117) = 5.51$, $p = .021$, ηp2 = .045, $M_{diff} = 8.44$, SE = 3.60.

Discussion

This study investigated the video camera features of online social platforms during a live public speaking task for people high in social anxiety. We created a naturalistic experimental paradigm in which participants would prepare and deliver a short speech in an online videoconferencing session. We manipulated the self-depicted live video of participants to account for internal focus (self-focus) and dummy audience images to account for the external social information. The objective of this study was twofold: firstly, we sought to replicate the findings of the well-established psychosocial stress protocols for evoking anxious arousal for online social platforms during a naturalistic speech task for socially anxious samples. Secondly, we expected the anxious arousal induced during the online speech task to be the highest when viewing a self-depicted live video feed as well as the audience profile images, especially just prior to public speaking performance.

Our main finding was that an online videoconferencing task can induce sufficient anxious arousal for people high in social anxiety, yielding effects larger than η2p = .207. This finding is consistent with meta-analytic estimates for socially evaluative encounters (Dickerson & Kemeny, 2004) In addition, although state anxiety was induced during the online task and reduced significantly upon leaving the online session, with no lasting anxiogenic effects, the levels of state social anxiety showed an opposite pattern, with increases after the online session. No evidence was found that audience profile photos combined with a live self-depicting video feed of the participants would cause heightened state anxiety. However, our findings suggested that certain combinations of audience image and participant video feed manipulation during a challenging online task might lead to more dysfunctional operation of some maintenance mechanisms (i.e., negative performance evaluations from self and other perspectives, and negative post event processing). However, we did not observe any meaningful differences in some other mechanisms (positive and negative affect, observer/field perspective switch) across different combinations of online social platform functions (profile photo/camera manipulations). We will discuss each finding in turn and then discuss the overall findings at a conceptual level in relation to the maintaining mechanisms of social anxiety.

Audience Profile Images and Speaker Video Feed on State Anxiety and State Social Anxiety

We found a marginal effect that when the live video feed of the speaker was available, it led to heightened levels of situational anxiety (main effect of Speaker on SUDS scores, p = .045). This provides some support for Clarks' model (Clark & Wells, 1995), which predicts impaired processing of the external environment whilst the internal focus on the experienced state anxiety is prioritised. However, this interpretation may be considered somewhat assertive, as our study did not include a comparison against participant videos or audience images in isolation.

There was no evidence that the combined effects of enhanced self-focus via live video feed and viewing audience images during an online speech task would increase anxious arousal through time. This is against the empirical and theoretical support for our prediction. That is, the prior work indicated that self-depicted video mechanisms may enhance self-focus (Vriends et al., 2017), and there is biased information processing of external social information existing for people with social anxiety (Chen, Short, et al., 2020; Rapee & Heimberg, 1997; Wong et al., 2020). However, our current null findings can be explained by several arguments. First, our design did not include live confederates and instead used dummy audiences as an external social threat This decision was made to facilitate the development of an online socially evaluative paradigm with little effort required from any research team, thus enabling its adoption for future research. However, this also meant that the primary manipulation did not involve an audience presence, unlike in other studies. In our design, there was an audience in both conditions, but the distinction lied in whether the person was represented by a photo or a profie imge silhouette. Secondly, although online social platforms simulate a live face to face interaction, some differences in online and in-person interactions exist. It has been noted that the sensory information conveyed over online social platforms is typically constrained, including poorer and less precise visual and auditory information (Parkinson & Lea, 2011). Additionally, the lack of physical presence seen on online platforms might reduce the sense of social presence and salience of the other person (Croes et al., 2016). Given that the situational anxiety experienced is assumed to be related to the processing of non-verbal social cues (e.g., audience behaviour) by the prominent cognitive theories

(Heimberg et al., 2010), diminished nonverbal cues of online social platforms might have invalidated the potential camera features in exaggerating cognitive biases for the socially anxious. Indeed, Nanamori et al. (2023) reported that audience gaze as a non-verbal behaviour is strongest in its prediction of social anxiety over other variables such as the speaking environment, the authority level, or familiarity with audience. Therefore, it might be that the camera features of online platforms might not activate cognitive biases of social anxiety due to the potential limitations in conveying visual information. In addition, we only relied on self-reporting measures. A recent study that examined the combined effects of internal focus and external threat on *attentional* processes showed visual stimuli to participants as internal and external threats in the forms of 'feedback waves' on a screen, while participants were giving a speech looking at the feedback waves (Lin et al., 2021). Participants were shown a pre-recorded video of an audience to make them believe that the feedback was coming from an actual audience. External feedback waves included positive (upward trend), neutral (stable trend), and negative (downward trend), and participants were trained for the meaning of these. Internal focus was the physiological waves of the participant (i.e., heart rate, skin conductance), again depicted on the screen during the talk. Participants showed a more pronounced attention to internal focus rather than external focus (measured by eye gaze). In our case, because we measured the state anxiety via self-report questionnaires and did not measure attentional processes utilising other forms of response input (e.g., eye tracking), it is not certain to conclude on the *relative* balance of the internal and external focus. Incorporating such techniques into this current naturalistic research design where the combined internal and external biases were examined might therefore be more informative, eventually leading to a more comprehensive understanding of the effect of video feedback features on state anxiety as a social anxiety maintenance mechanism.

Second, it has been indicated that the extent of dysfunctional biases developed by individuals with social anxiety may be influenced by the severity level of their condition (Bantin et al., 2016). For example, Vriends et al. (2017) recently studied the potential to enhance the internal focus mechanisms of social anxiety within online platforms. Through an equally sized video screen, women with social anxiety diagnoses and subclinical social anxiety engaged in live conversations with a male confederate in four distinct conversation settings (warm up, positive, critical, and active). They measured how long participants looked at their own and the confederate's videos. During the 'critical' period, people with sub-clinical anxiety observed their video feedback more frequently. For those with a diagnosis of social anxiety, more frequent dwelling on their video feedback included all four parts of the conversation task. The results suggest that online platforms can activate cognitive biases in individuals with social anxiety, but the degree of activation may depend on the severity of their social anxiety. Although our sample characterised a population high in social anxiety using a well-established questionnaire using SPIN (Connor et al., 2000), it warrants replication using a clinical sample.

We observed that a challenging socially evaluative task performed on online social platforms increased subjective state anxiety for people high in social anxiety (irrespective of camera manipulation). This is consistent with previous work where anxiogenic protocols were tested on a healthy sample in real life (Kirschbaum et al., 1993), through a pre-recorded screen (Hawn et al., 2015), in virtual environments (Shiban et al., 2016), and online via videoconferencing platforms (Eagle et al., 2021). These findings complement the findings from recent online anxiety induction protocols tested on socially anxious samples (Huneke et al., 2022; Miller et al., 2021). Further, participants reported a significant increase in state *social* anxiety upon leaving the online session, as opposed to a decrease in state anxiety. This could reflect the post-event processing of the disorder (will be discussed later), where people with SAD tend to ruminate more in the aftermath of a social interaction (Dannahy & Stopa, 2007), which might indirectly provide a link between *state social* anxiety and post-event processing among socially anxious people within online platforms.

Audience Profile Images and Speaker Video Feed on Performance Evaluations

We found evidence that performance evaluations were the most negative when no audience images were available, and participants saw their video-feed. However, the participants reported comparable performance evaluations whether they had their video feed on or off, if audience images were on. One possible explanation for why the absence of audience images coupled with the live video feed would result in worse performance evaluations could be the link between social anxiety and 'uncertainty'. There is a strong link between social anxiety and intolerance of uncertainty (Boelen & Reijntjes, 2009; Carleton et al., 2010), especially on the domains of uncertainty related to negative behavioural and *self-refence implications* (e.g., being uncertain means that I lack confidence), rather than its relation to a general worry (e.g., it is unfair having no guarantees in life) (Counsell et al., 2017). Therefore, the uncertainty of the external threat information (i.e., the absence of audience images while they are *still* there) might feed into enhanced self-focus (i.e., participant video feed) on online platforms and trigger dysfunctional underestimates. Although theories of social anxiety (Rapee & Heimberg, 1997; Wong & Rapee, 2016) suggest that people with social anxiety monitor external and internal information simultaneously leading to underestimates of their social performance, due to the illusion of online platforms (i.e., although no audience images are present, audience is *still* there), the presence of audience images or videos might therefore be an *adaptive* mechanism during an *online* live conversation for the socially anxious, especially when the user had their live video feed available to others. Looking from external ratings data, although participants gave worse performance evaluations of themselves under certain combinations of video feedback, the camera manipulations did not lead to *actual deficits* of their performance (i.e., rated by the experimenter). This might imply that the camera features of online platforms do not necessarily influence the actual performance, but these features might lead to performance underestimations during a social performance. This finding is in line with available empirical evidence (Brozovich & Heimberg, 2011; Cheng et al., 2017; Perini et al., 2006; Spurr & Stopa, 2003). However, there is also available evidence suggesting that people with social anxiety present actual performance deficits (Cheng et al., 2017; Norton & Hope, 2001; Stopa & Clark, 1993; Voncken et al., 2008). Further, Voncken and Bögels (2008) reported that performance deficits for socially anxious people were observed during a conversation task but not during a *speech* task. The authors concluded that social interactions that require more interpersonal skills (e.g., conversation) might elicit more social performance deficits, while situations where a performance is required (e.g., speech) would result in more cognitive distortions among the socially anxious. Since we employed a speech task, our findings might suggest that regardless of any manipulation of camera settings, people high in social anxiety might not exhibit any performance deficits but may present cognitive distortions (*perceived* negative performance) regarding their performance during online performance interactions. Future work might utilise a conversation scenario for investigation.

Audience Profile Images and Speaker Video Feed on Post-event Processing

Our findings suggest that the absence of audience images during the online speech task led to more severe ruminations about the online social interaction, but only when participants were able to view their video feed. When participants had access to audience images, comparable levels of post-event processing were observed regardless of whether they viewed their video feed or not. In the literature, it has been shown that post-event processing has positive associations with trait social anxiety (Kocovski et al., 2005), and is involved in the interplay between cognitive biases and state social anxiety (Gaydukevych & Kocovski, 2012). Importantly, findings from other studies suggest that post-event processing following enhanced SFA maintains (Brozovich & Heimberg, 2011; Penney & Abbott, 2014). Our findings provide evidence that, on online platforms, the presence of audience video feedback might be an adaptive component to decrease the magnitude of SFA in which people with SAD engage, leading to less severe post-event processing.

Audience Profile Images and Speaker Video Feed on Observer/Field Perspective

Under different manipulations of camera features (video feed or profile images on/off), we found no evidence of an ‘observer’ perspective taken. In fact, numerical representations (but not statistical) showed that all combinations of groups reported a ‘field’ perspective in relation to their online performance. This contrasts with empirical evidence reporting on the use of ‘observer’ perspective among socially anxious individuals and also reporting a significant shift to an ‘observer’ perspective during socially evaluative situations (George & Stopa, 2008; Wells et al., 1998; Wells & Papageorgiou, 1999). As no previous work has investigated how perspective taken would alter on online social platforms, one possible explanation of our findings might be in relation to the real-life theories of social anxiety. Clark et al. (1995) mentioned a ‘baseline image’ that socially anxious people were assumed to have in their mind that is often connected to a negative past experience of a social situation (Hackmann et al., 2000). This negative self-image is assumed to be replayed, which can take the form of an ‘observer’ perspective (Clark, 2001). Although we do not have access to this data, it is worth noting that previous work (Meral & Vriends, 2022) reported no links between negative self-image and SFA using an online conversation scenario. However, investigating this link could be useful in explaining observer perspective within our online public speaking paradigm, especially given that public speaking is commonly observed in socially anxious samples (Bögels et al., 2010) and in the general population (Stein et al., 2017). An alternative explanation of our findings could be based on the work of Coles et al. (2002), who reported that perspective taken might depend on the level of social anxiety and time that has passed since the social event. In their study, participants gave an impromptu speech and rated their level of perspective during the speech and three weeks later. Over the three-week interval, socially anxious participants’ perspective shifted more toward the observer. Replicating this study, where perspective is measured over time in consideration with other potential cognitive distortions, might give a more precise understanding on how perspective is taken on online platforms under different camera manipulations.

Audience Profile Images and Speaker Video Feed on Negative and Positive Affect

Positive or negative affect did not differ under the various combinations of video feedback during a speech on online platforms. Although social anxiety is linked with high negative affect and low positive affect (Kashdan, 2007) and negatively impacted mood in socially evaluative online paradigms (Huneke et al., 2022), it should be noted that we assessed pre affect before the participants entered the online session and post affect once they had left the online session. This approach might have limited the usefulness of our data in capturing affective states.

Limitations

We should note our methodological limitations. Our manipulation checks revealed comparable self-awareness on different combinations of video feedback features. This could be due to several reasons. First, following the online videoconferencing session, we recorded retrospective self-awareness. According to Hauser et al. (2018), both the manipulation check and the manipulation itself may have an effect on the manipulation check. Given the difficulty of our task (speech performance), participants’ awareness might be confounded by the effects of induced anxiety. In addition, although our Audience manipulation included having the profile pictures on or off, the dummy audience was still ‘present’ in the online session and might have had an impact on the manipulation check. An earlier study (not using online platforms) examined whether the presence of a judging jury was necessary to cause stress in healthy males. The physiological stress levels of individuals who completed the task in front of a visible jury and those who completed it while the jury was hidden behind a one-way mirror did not differ significantly (Andrews et al., 2007). This could indicate that just *being aware of* the presence of an audience is sufficient to set up a stressful social-evaluative environment. As mentioned previously, we did not test our hypotheses on a clinical patient sample diagnosed with social anxiety, thus our results cannot be generalised to clinical populations. In addition, we did not exclude participants if they had any current psychiatric diagnoses or any significant physical illness. These criteria can affect the stress protocol outcomes (Linares et al., 2020). Since we did not include a control group consisting of individuals with low social anxiety, it remains possible that the observed significant effects (e.g., negative performance evaluations, post-event processing) could diminish or become non-existent when compared to such a control group. We utilised a naturalistic online speech task, however, there are other factors which were not controlled (e.g., internet connection speed, participant distraction by other members of the household). Although we instructed participants to minimise the distracting factors in their surrounding area during the experiment, such disadvantages should be noted.

Strengths and Implications

Despite the limitations, we were able to examine the anxiogenic reactivity sensitively in different phases of a social task (e.g., anticipation, speech) as well as to explore cognitive biases of social anxiety within an online social encounter. In addition, an exclusively online approach might have reduced the confounding effects of experimenters as well as laboratories, allowing a more naturalistic investigation. As online communications platforms have now been extensively used for many purposes, including educational lectures, job interviews (Chapman & Rowe, 2001), and internet-delivered therapies (Boettcher et al., 2013), information on how videoconferencing platforms function for people with high social anxiety could help optimise these platforms for such vulnerable people. In particular, due to the dysfunctional cognitive processes in which people with social anxiety engage, video feedback is a common technique that is often used to correct these biases of the socially anxious (Chen, Mak, et al., 2015; Chen et al., 2018). Our findings suggest that post-event processing and *perceived* performance evaluations might be distorted under certain camera manipulations on online platforms. Therefore, video feedback programmes might be refined, placing more emphasis on negative performance evaluations and post-event processing.

The present study underlines the following research implications. As noted previously, utilising other response inputs (e.g., eye tracking) or physical measures (e.g., smart phone based photoplethysmography (Harvie et al., 2021) might give a more thorough understanding of the camera functions on online platforms and their relation to the cognitive biases of social anxiety. For the Audience images, we used one live video feed for the moderator (neutral expression), and the rest of the audience images included static photos (also neutral in appearance). There is evidence that socially anxious individuals discriminate for negative stimuli even when a neutral or positive stimuli is included (Perowne & Mansell, 2002). Although previous work used pre-recorded videos to explore this interpretation bias (Chen, Thomas, et al., 2015), it was tested neither on online platforms nor combining external stimuli with the internal focus mechanism. Future studies might incorporate pre-recorded videos of an audience while manipulating the speaker video feedback feature on online platforms during a socially evaluative task. In addition, as the video interface appears to intersect with experienced social anxiety (Miller et al., 2021), testing the cognitive mechanisms of social anxiety on online platforms could be extended to different interfaces, such as feedback equal in size or group chat layouts.

Conclusion

In conclusion, this study provides a new framework for a naturalistic online experimental paradigm to test for cognitive biases of social anxiety. The interface on different combinations of one's video feed and audience images did not influence the levels of state anxiety during an online public speaking task. We suggest that due to attenuated non-verbal cues during online social interactions, the theoretical concept of the cognitive biases of social anxiety may not be conveyed via camera manipulations on the interface. However, our results provide support for the potential of online stress protocols for evoking anxious arousal, in particular for sub clinical social anxiety groups. In addition, we discovered a cognitive mechanism of perceived negative performance evaluations and negative rumination among socially anxious individuals when performing on online platforms. We suggest that, when communicating online, being able to view audience images or videos might be an adaptive mechanism.

Chapter 5 – General Discussion

5.1. Chapter Overview

This section will review the rationale of this thesis, followed by a summary of the key findings. Subsequently, it will provide detailed explanations of the critical issues related to these findings, including the effects of the proposed paradigms on anxious arousal and social anxiety biases. The subchapters will discuss findings with reference to theoretical, clinical, and research literatures. The limitations of the empirical chapters will also be addressed, and recommendations will be provided to guide future research in this area.

5.2. Review of the Aims and Summary of Key Findings

Social anxiety is a complex condition that is characterised by cognitive biases before, during and after socially evaluative situations (Clark et al., 1995; Heimberg et al., 2010; Hofmann, 2007; Rapee & Heimberg, 1997). These biases include information processing of self and the social environment, and repetitive negative thinking prior to and after socially evaluative situations (Wong et al., 2019, 2020; Wong & Rapee, 2016). The popularity of online social communication platforms has skyrocketed, and this has become an integral part of daily social interactions, in particular after the COVID-19 pandemic (Wiederhold, 2021, 2021). Likewise, the use of virtual reality (VR) to study anxiety-related disorders, including but not limited to therapeutic or diagnostic means, has grown (Carl et al., 2019; Helminen et al., 2019; Kelly et al., 2007; Lindner et al., 2019; Maples-Keller et al., 2017; Shiban et al., 2016; Wiederhold, 2016). The testing of online social communication platforms as anxiogenic paradigms is relatively new (Eagle et al., 2021; Gunnar et al., 2021). A socially evaluative paradigm delivered online is suggested to result in higher levels of anxious reactivity compared to the paradigms without a social evaluation component (DuPont et al., 2022; Harvie et al., 2021), however, further testing is needed to investigate how online communication platforms, activate real-life theories of social evaluative anxiety.

This thesis reported three experimental chapters that examined social anxiety in virtual/online social environments focusing on the effects of audience presence, and investigated social anxiety related biases including anticipatory and post-event processing, and performance evaluations during these virtual/online social encounters. Experiment 1 (Chapter 2) investigated the combined effects of CO_2 gas and a virtual audience on inducing anxious arousal, and anticipatory processing and performance evaluations. Experiment 2 (Chapter 3) developed a photorealistic virtual scenario using a pre-recorded audience to assess its anxiogenic potential on subjective (state anxiety and state social anxiety) and objective arousal. We also investigated the sensitivity of this paradigm to individual differences in trait social anxiety, and examined its effects on post-event processing and performance evaluations. Experiment 3 (Chapter 4) recruited people with high social anxiety to validate an internet-delivered, live anxiogenic protocol, and compared the camera feed features (Audience/Speaker on/off) during an online socially evaluative performance task. We also tested how the groups would differ in post-event processing and performance evaluations, depending on camera feed features (on/off). The findings, summarised in Table 18, provided some support for study hypotheses and suggest that these paradigms, when an audience is present, have the potential to induce anxious arousal in social-evaluative environments, in both online or virtual delivery modes.

5.2.1. Question 1: Can Digital Socially Evaluative Paradigms Induce Anxiety?

As shown, Table 18 provides evidence of increases in both objective and subjective anxious arousal for the combined virtual audience and gas effects. This finding might suggest that the combination of internal self-relevant cues (i.e., increased heart rate) via the CO_2 gas and external social cues (i.e., virtual audience) may be optimal for inducing anxiogenic effects in socially evaluative paradigms (Heimberg et al., 2010). It is noteworthy to mention when the participants inhaled normal room air and subsequently presented either to a virtual audience or in an empty lecture hall, these scenarios yielded comparable subjective and objective anxious arousal. Therefore, we concluded that a mere socially evaluative scenario with no audience inclusion within a virtual paradigm might not be sufficient to induce anxious reactivity. However, our findings differ from some previous evidence that showed higher cortisol and cardiovascular effects in tasks like TSST or public speaking compared to their control versions without social evaluation (Kothgassner, Felnhofer, et al., 2016; Kothgassner et al., 2021). Yet, Dickerson et al. (2008) provided empirical evidence that if an audience is non-attentive during a social interaction scenario, the desired anxiogenic reactivity (i.e., cortisol) is not observed relative to an attentive audience. Although we used dynamic stimuli that were attentive to the speaker, our avatars consisted of cartoon-like characters. Potentially, the realism of avatars could have resulted in a lack of negative evaluation from the virtual audience, resulting in comparable anxious reactivity when faced with virtual audience or a virtual empty lecture hall (air conditions). Indeed, we did not observe any differences in presence felt in the virtual paradigm for these two air-inhaled groups within our data. Presence is considered to be an important factor in eliciting anxious reactivity in socially evaluative virtual protocols (Kothgassner, Hlavacs, et al., 2016), and it has been linked to the level of immersion (Diemer et al., 2015). Therefore, we thought that creating a virtual experience that closely resembles real-life situations might help to generate the anxious reactivity that we did not observe in Experiment 1. We improved our virtual scenario with a pre-recorded audience that would presumably result in a more immersive experience (Experiment 2). However, we also failed to find meaningful differences in anxiogenic reactivity between an audience-populated virtual scenario and a non-populated virtual scenario on state anxiety and heart rate (although we observed numerical differences). There are two possible

Table 18

Summary of the Key Findings

			Experiment 1 (Chapter 2)	Experiment 2 (Chapter 3)	Experiment 3 (Chapter 4)
		Groups	CO_2 inhalation and virtual audience* Air inhalation and virtual audience Air inhalation and empty VR	Virtual audience* Empty virtual lecture room	Speaker camera on & Audience images on* Speaker camera on & Audience images off Speaker camera off & Audience images on Speaker camera off & Audience images off
Key Findings	Subjective	Group comparison	GAD-$7_{Modified}$ ↑ SUDS ↑	GAD-$7_{Modified}$ X SUDS X $SASCI_{Modified}$ ↑	GAD-$7_{Modified}$ X SUDS X SASCI X
		Main effect of Time	GAD-$7_{Modified}$ ↑ SUDS ↑	GAD-$7_{Modified}$ ↑ SUDS ↑ $SASCI_{Modified}$ ↑	GAD-$7_{Modified}$ ↑ SUDS ↑ $SASCI_{Modified}$ ↑
	Objective	Group comparison	Heart rate ↑	Heart rate X	-
		Main effect of Time	Heart rate ↑	Heart rate ↑	-

		Experiment 1 (Chapter 2)	Experiment 2 (Chapter 3)	Experiment 3 (Chapter 4)
	Groups	CO_2 inhalation and virtual audience* Air inhalation and virtual audience Air inhalation and empty VR	Virtual audience* Empty virtual lecture room	Speaker camera on & Audience images on* Speaker camera on & Audience images off Speaker camera off & Audience images on Speaker camera off & Audience images off
Cognitive Factors of SAD	Performance Evaluations	More negative performance evaluations of participants Observer ratings are comparable	Comparable performance evaluations of participants Observer ratings are not recorded	More negative performance evaluations of participants (for Speaker camera on & Audience images off) Observer ratings are comparable
	Anticipatory Processing	More severe anticipatory processing	-	-
	Post-event Processing	-	Comparable post-event processing	More frequent negative post event processing (for Speaker camera on & Audience images off)
Exploratory Findings	Mood	Negative affect ↑ Positive affect ↓	Negative affect X Positive affect X (No significant interaction or main effects)	Negative affect X Positive affect X (No significant interaction or main effects)
	Anxiety Sensitivity	↑	X (No significant interaction or main effects)	-
	Panic Symptomology	↑	X (No significant interaction or main effects)	-

		Experiment 1 (Chapter 2)	Experiment 2 (Chapter 3)	Experiment 3 (Chapter 4)
	Groups	CO_2 inhalation and virtual audience* Air inhalation and virtual audience Air inhalation and empty VR	Virtual audience* Empty virtual lecture room	Speaker camera on & Audience images on* Speaker camera on & Audience images off Speaker camera off & Audience images on Speaker camera off & Audience images off
Notes	Presence (VR)	Overall scale ↓	No effect for overall scale X Realism subscale ↑	-
		-	A borderline trend for trait social anxiety relevance to this paradigm, *p* =.094. Visual trends related to the habituation effects of anxiogenic VR in a real-life social situation, *p*s>.490 for subjective anxiety, *p* = .092 for heart rate	-

Note. * denotes the reference groups that were compared against the other groups when creating this table. GAD-$7_{Modified}$ = Generalised Anxiety Disorder Assessment, SUDS = Subjective Units of Distress Scale, $SASCI_{Modified}$ = Modified Social Anxiety Session Change Index. GAD-$7_{Modified}$ includes four of the original seven items and measured on a five-point Likert scale for Chapter 4 experiment. ↑ indicates significant increase and ↓ indicates significant decrease. X indicates no significant difference.

explanations that may account for these comparable differences in anxiogenic reactivity. The first explanation is that a *photorealistic* virtual environment even *without* an audience might have elevated anxious arousal, speculatively due to its resemblance of a real-life social event, resulting in a lack of significant effects between our manipulation groups (Audience absent, present). The second explanation pertains to limitations in our study, specifically the lack of proper screening for participants' psychiatric illnesses, which could potentially confound the data, although we made efforts to characterise group differences with diverse baseline trait measures. Our online socially evaluative paradigm demonstrated a significant increase during the speech task, accompanied by decreases, before returning to baseline levels. This suggests that online videoconferencing platforms have the potential to induce anxious arousal, but it should be acknowledged that we used a sample high in social anxiety within our online paradigm, and did not assign a control group against which to test these effects.

5.2.2. Question 2: Can Digital Socially Evaluative Paradigms Resemble Social Anxiety?

We found that giving a talk to an audience within our photorealistic paradigm increased *state* social anxiety compared to presenting in an empty virtual room. Likewise, participants with high levels of social anxiety reported elevated subjective anxiety when giving a talk in an online videoconferencing session. These findings support the relevance of socially evaluative paradigms to situational social anxiety, as asserted by previous work (Huneke et al., 2022; Rapee & Abbott, 2007).

In our studies, we focused on performance evaluations and anticipatory and post-event processing, as these are crucial contributors to social anxiety in socially evaluative situations (Modini & Abbott, 2016; Wong et al., 2020). Looking at Table 18, we found that our augmented paradigm that incorporated CO_2 gas and a virtual audience resulted in underestimations of performance and increased severity of anticipatory processing. Additionally, in the context of public speaking during online videoconferencing sessions, we observed a higher frequency of post-event processing when participants were able to see their self-depicting video in the absence of audience images. These findings contribute to our understanding of online and virtual socially evaluative paradigms and their link to social anxiety cognitive mechanisms. These insights provide a foundation for various implications, which will be discussed in detail later.

5.2.3. Exploration: How Do Our Digital Platforms Compare as Anxiogenic Paradigms?

In a supplementary synthesis, we compared our three socially evaluative paradigms and their impact on peak anxiety levels during public speaking tasks. As summarised in Table 19, the groups compared were: (a) a virtual audience with regular air combination; (b) a photorealistic virtual audience; and (c) an online videoconferencing

Table 19

A Comparison of Increases in Peak Anxiety Over Baseline in Percentage and Effect Sizes for Three Digital Socially Evaluative Platforms

Study Chapter	Socially Evaluative Threat	Digital Platform	Sample	Subjective Anxiety % (Cohen's *d*)			Objective Anxiety % (Cohen's *d*)
				GAD-7*Modified*	**SUDS**	**SASCI*Modified***	**Heart Rate**
Chapter 2	72 dynamic cartoon-like avatars	Virtual Reality (Oculus Rift)	n=31 (subjective arousal) n=24 (objective arousal) Healthy (screened)	+78.09 (1.11)	+60.69 (1.22)	-	+13.20 (1.09)
Chapter 3	21 pre-recorded real persons	Virtual Reality (Oculus Rift)	n = 32 General (no screening)	%43.28 (0.61)	%43.98 (0.84)	%46.92 (0.76)	+12.26 (0.68)
Chapter 4	20 static real-life profile images and one dynamic audience video (moderator)	Online (Blackboard Collaborate)	n = 29 High in Social Anxiety	%44.53 (0.83)	%29.49 (0.66)	%34.52 (0.65)	-

Note. GAD-7$_{Modified}$ = Generalised Anxiety Disorder Assessment, SUDS = Subjective Units of Distress Scale, SASCI$_{Modified}$ = Modified Social Anxiety Session Change Index. GAD-7$_{Modified}$ includes four of the original seven items and measured on a five-point Likert scale for Chapter 4 experiment. Effect size of *d* $(M2 - M1)/SD_{\text{pooled}}$ is reported.

session using data from the group that did not have access to their self-depicting video but were able to view audience images or videos. Although slight differences arose in terms of methodology[16], the most notable finding was that a cartoon-like virtual audience resulted in a doubled effect size on anxious reactivity. This outcome is surprising since one would anticipate higher anxiety levels in a photorealistic VR setting due to its resemblance to real-life. Our interpretation is that the involvement of face masks worn by participants in the cartoon-like virtual group (for the purpose of Experiment 1) may have intensified the anxiety effect. On the other hand, our online paradigm resulted in the lowest levels of anxious reactivity, although it was conducted live. This could potentially be the result of the greater immersive effect of virtual environments, as opposed to a videoconferencing experience of a flat screen. In addition, the online paradigm we developed was conducted exclusively online, whereas the two VR studies were conducted at research laboratories. It is possible that participants in the VR studies experienced slightly higher levels of anxiety due to the unfamiliarity of the laboratory environment and the research team, compared to the participants who took part in the live videoconferencing session from the comfort of familiar surroundings. In addition, it is important to note that the pixel quality during the online interactions was not under the control of the experimenter due to technical problems that might arise (i.e., internet speed). This variability in pixel quality could also explain the observed smallest effect sizes in peak anxiety for the online public speaking task, as the interpretation of non-verbal expressions is an important contributor to the severity of social anxiety (Chen, van den Bos, et al., 2020). Nevertheless, both virtual and online paradigms we proposed generated anxious arousal (with Cohen's *d*'s ranging from 0.65 to 1.22) that were comparable to real-life anxiogenic estimates of effects (Cohen's d = 0.67) (Dickerson & Kemeny, 2004). One issue to consider would be exploring alternatives to a hypercapnic challenge (CO_2) given the time and budget-related resources it consumes, although the capability to mimic anxiety in laboratories is valuable for translational research.

5.3. Implications

5.3.1. Theoretical Implications

Through our *online* socially evaluative paradigm, we established that some cognitive mechanisms of social anxiety (i.e., performance evaluations, post-event processing) are negatively biased among people high in social anxiety; for example, when exposed to their self-depicting (self-referential) video without seeing the audience images. The processing of the self (i.e., self-focused attention, self-beliefs) plays a crucial role in

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[16] Our online paradigm was tested on people high in social anxiety. For our photorealistic virtual scenario, we did not utilise any screening (e.g., psychiatric conditions), whereas the study where we tested the cartoon-like virtual audience included a strict screening procedure.

the onset and prognosis of SAD (Gregory & Peters, 2017; Gregory et al., 2016). Therefore, our finding suggests that the processing of the self might be sensitive to camera settings in online communication platforms. This extends the current literature by providing evidence that cognitive mechanisms in social anxiety are differentially activated by characteristics of the online social interface/environment. Likewise, testing anxiogenic effects within virtual socially evaluative paradigms may significantly improve our understanding of how social anxiety mechanisms operate in virtual environments. For example, Dechant et al. (2017) suggested that VR has the potential for use as diagnostic tool for social anxiety by measuring maladaptive cognitive biases that feature in dominant cognitive theories (Clark, 2001; Clark & Wells, 1995; Heimberg et al., 2010; Rapee & Heimberg, 1997). Thus, digital anxiogenic paradigms can further validate and enhance the applicability of such diagnostic tools.

5.3.2. Treatment Implications

First, while we claim that our proposed paradigms might assert a relevance to social anxiety based on cognitive theories, it should be noted that current diagnostic practices may present a limited understanding of SAD. That is, social anxiety is accompanied by comorbidity with other psychotic disorders, with a prevalence rate exceeding 20% (McEnery et al., 2019), which might result in varying symptomology along a spectrum. Our paradigms serve as practical tools that offer advantages in modifying specific cognitive domains that require attention during therapies for social anxiety. For example, a study conducted by Mesri et al. (2017) reported that people with social anxiety who exhibited avoidance traits showed greater benefit from Cognitive Behavioural Therapy (CBT) compared to third-wave therapies such as Acceptance and Commitment Therapy (ACT) at a 12-month follow-up. This highlights the need for tailored interventions, and our evidence-base paradigms can serve as a proof-of-concept in adapting them for such therapeutical purposes. Second, utilising virtual and online platforms for therapeutic efforts might be especially well-suited and advantageous for people with social anxiety (Emmelkamp et al., 2020; Pelissolo et al., 2019; Powers et al., 2008). Prior work provides evidence supporting this claim, as studies have shown that VR-based exposure therapies (VRET) exhibit slightly lower attrition rates compared to in-vivo therapy modalities for anxiety disorders (Benbow & Anderson, 2019). In addition, the refusal rate for VRET has been found to be significantly lower, reported at 3%, in contrast to the higher rate of 27% observed in in-vivo exposure therapies (Garcia-Palacios et al., 2007). Likewise, communicating via online social platforms has been favoured among people with social anxiety (Hutchins et al., 2021), and has resulted in lower perceived social anxiety relative to in-person social interactions (Yen et al., 2012). Given the extensive accessibility of digital technologies in the field of mental health interventions (Fairburn & Patel, 2017), our socially evaluative paradigms have the potential to provide valuable insights that can inform and enhance existing digital therapies for social anxiety.

5.3.3. Laboratory Research Implications

The symptomology of social anxiety can vary between Western and Eastern cultures (Nagata et al., 2015; Sakurai et al., 2005), as also emphasised within the revised edition of the DSM 5 (American Psychiatric Association, 2022). For example, 'Taijin Kyofusho' is a subtype of social anxiety prevalent in Japanese and East Asian cultures, manifested by fear of offending *others* (D'Avanzato & Dalrymple, 2016). This expands the scope of typical social anxiety that primarily revolves around concerns about personal humiliation or rejection (American Psychiatric Association, 2013). In addition, according to a meta-analysis by Miller and Kirschbaum (2019), the variance in cortisol responses during cross-national evaluations of a TSST was found to be predicted by cultural and systematic differences between countries (e.g., peace versus ambition). Our digital socially evaluative paradigms, which have been shown to elicit anxiety responses, can serve as a standardised tool for conducting cross-cultural testing of social anxiety across diverse cultures. In addition, high prevalence of social interaction fears has been reported in the community samples in the United States (Stein et al., 2000) and in developing and developed countries (Stein et al., 2010), whilst socially evaluative situations (i.e., giving a speech or speaking in public, speaking in a meeting or class) account for the most common feared social situations among other fears (e.g., talking with strangers). Our investigations into novel photorealistic VR can further open the way for explorations of socially evaluative situations within non-clinical populations.

5.4. Limitations and Future Directions

First, regarding sample characteristics, we used a cut off score >15 for Social Phobia Inventory (SPIN) (Connor et al., 2000) to quantify people with high social anxiety for our online paradigm. Although SPIN is a well-established questionnaire with good reliability (Antony et al., 2006), the cognitive mechanisms of social anxiety might exhibit differently to socially evaluative threat based on social anxiety severity. For instance, Chen, van den Bos, et al. (2020) conducted a study that examined visual avoidance behaviours in people with varying levels of social anxiety across different socially evaluative scenarios, including computerised face tasks, public speaking tasks, and social interactions. The findings revealed that individuals with a social anxiety diagnosis exhibited visual avoidance in all socially evaluative scenarios. However, high levels of social anxiety were specifically associated with avoidance of public speaking and social interactions, but not with computerised face tasks. Their findings imply that our paradigm, which involves a socially evaluative audience delivered through online platforms, warrants further testing on clinical social anxiety samples to understand better how social anxiety manifests in online settings.

Secondly, it should be noted that in our photorealistic virtual paradigm we did not screen for medication use, tobacco use, caffeine consumption levels or menstrual cycle among participants. This is a potential limitation, as certain medications can influence cardiovascular responses and potentially confound our findings (Kudielka et al., 2007; Kudielka et al., 2009). Further, we did not consider the timing of the testing sessions. Research conducted by Kudielka et al. (2004) indicated that cortisol responses during a TSST protocol were significantly higher when tested in the morning relative to testing in the afternoon, after controlling for age and gender.

Lastly, we used non-invasive, publicly available non-medical devices for measuring heart rate levels. Although smart wearables are nowadays being widely used in laboratory research (Castaneda et al., 2018; Henriksen et al., 2018; Nelson et al., 2020), previous research has suggested that motion artifacts (e.g., hand movements) and elevated heart rate levels might lead to greater discrepancies between smart wearables and gold standard electrocardiogram (ECG) recordings (e.g., BIOPAC) (Alfonso et al., 2022; Bent et al., 2020; Müller et al., 2019). Further, Benedetto et al. (2018) conducted a study using the Fitbit Charge 2, which is the same equipment we used, and compared it to a reliable ECG measurement while participants were cycling on a stationary bicycle. The findings indicated that the Fitbit Charge 2 might overestimate heart rate levels almost by 17 bpm and underestimate them by 30 bpm. This is an important consideration, since in our studies participants may have exhibited reflexive hand movements during their public speaking tasks, potentially leading to motion artifacts and less reliable heart rate measurements. Future work could utilise non-invasive devices that could be worn in areas with minimal movement (e.g., earlobe, forehead) (Gnacek et al., 2022).

Regarding future work, in terms of the portrayal of our *online* paradigm in involving the audience as real people (based on what participants were told), previous research with a similar experimental design using pre-recorded audience stimuli found similar patterns for attentional processes in SAD, regardless of whether participants knew that the audience they were viewing was pre-recorded or consisted of actual people in another room (Chen, Thomas, et al., 2015; Lin et al., 2020). Testing this within a controlled setting would be useful in understanding the credibility of a dummy audience from the participants' perspectives and could provide insight into our proposed paradigms.

In developing experimental models of anxiety, Baldwin and Abou-Aisha (2019) listed a set of criteria, including the need for models to induce repeatable and consistent anxiogenic effects. Future work might investigate how robust the anxiety inducing effects of our paradigms are when tested over multiple days. In addition, these protocols tend to be less consistent for cortisol responses (Helminen et al., 2019), and thus the subjective, objective, and neuroendocrine responses do not correlate well (Frisch et al., 2015; Shiban et al., 2016). It is worth investigating neuroendocrine responses within our novel paradigms, and testing whether the responses are parallel to the subjective and cardiovascular responses. On top of these biomarkers, computational advancements now made it possible to integrate electroencephalography (EEG) measures into VR via dry electrodes (Miltiadous et al., 2022). Utilising these and examine how neural processes might be influenced during our anxiogenic would provide rich and complementary scientific evidence for the theory, intervention, and treatment of social anxiety (Bruehl et al., 2014; Cremers & Roelofs, 2016). For instance, Li et al. (2016) reported that certain pharmacological and psychological interventions impact different brain regions for people with SAD, using brain imaging techniques. Such testing could be especially valuable for the augmented CO_2/VR model we proposed (Chapter 2). Additionally, EEG studies have the potential to record data in a dynamic temporal fashion that can be integrated into VR (Miltiadous et al., 2022). The time-series approach has been encouraged by RDoC frameworks, suggesting that psychopathology is best described when viewed as dynamic processes over time (Frank et al., 2017). Given that we established the anxiogenic effect of the socially evaluative protocols we proposed, future work could utilise our paradigms to test anxiogenic reactivity for different and diverse biomarkers.

5.5. Closing Remarks

This thesis has contributed to the understanding of digital socially evaluative paradigms within the context of social anxiety. The methodology employed to convey social evaluation in this study is not only novel but is also timely, practical, and rather cost-effective. Developing reliable human-based anxiogenic models utilising technology could serve as a practical and standardised way for studying the onset and prognosis of anxiety disorders, including social anxiety, and could have the potential to pave the way for evidence-based and more precise intervention efforts that target the underlying mechanisms of anxiety related disorders.

Appendix A Exclusion Criteria List (Chapter 2)

Criterion	Criterion specification	Assessment (phone screen or lab day)	Decision (eligible or not eligible)
Age	Under 18 or over 55	Phone screen	Not eligible
Vision	Use of glasses for vision correction	Phone screen	Not eligible
Caffeine	>8 cups per day	Phone screen	Not eligible
Alcohol	>28 per week – males >21 per week – females History of alcohol dependence/abuse	Phone screen	Any = Not eligible
	Positive breath test	Lab day	Not eligible
Smoking	> 6 per day	Phone screen	Not eligible
Cardiovascular	Hypertension Cardiovascular disease	Phone screen	Any = not eligible
	BP > 140/90 HR less than 50, greater than 90bmp	Lab day	Any = not eligible
BMI	Less than 18, more than 28 OR weight less than 45 kg (7 stone)	Phone screen – reassessed in the lab day session	Not eligible
Pregnancy	Pregnant Breast feeding	Phone screen and reassessed in the lab day session	Not eligible
Depression	History or current diagnosis of bipolar/MDD	Phone screen	Not eligible
	3/3 of the depression questions on the MINI	Phone screen	Not eligible
Mania	History of mania	Phone screen	Not eligible
	2/4 questions on the MINI	Phone screen	Not eligible
Panic	2/2 of the panic questions on the MINI History or diagnosis of panic disorder History of panic attacks/hyperventilation attacks	Phone screen	Any = Not eligible
	2/2 of the anxiety questions on the MINI 1/1 of the agoraphobia 1/1 of the social anxiety disorder	Phone screen	Any = Not eligible
GAD	History or diagnosis of GAD	Phone screen	Not eligible
	2/2 of the GAD MINI questions	Phone screen	Not eligible
Agoraphobia	1/1 question on the MINI	Phone screen	Not eligible
Social Anxiety Disorder	1/1 question on the MINI	Phone screen	Not eligible

Criterion	Criterion specification	Assessment (phone screen or lab day)	Decision (eligible or not eligible)
OCD	1/1 question on the MINI	Phone screen	Not eligible
PTSD	History or diagnosis of PTSD	Phone screen	Not eligible
	3/3 Questions on the MINI	Phone screen	Not eligible
Addiction	Indication of drug abuse Illicit drug use in the last 8 weeks 1/1 question on the MINI (exceeding occasional - more than twice - use)	Phone screen	Not eligible
Family history	Family history of panic disorder/panic attacks	Phone screen and reassessed in the lab day session	Not eligible
Heart and lung disease	Includes diagnosis of asthma (childhood asthma is not included)	Phone screen	Not eligible
Diabetes	Treatment or diagnosis of diabetes	Phone screen	Not eligible
Migraines	History of migraines requiring treatment	Phone screen	Not eligible
Medication use	Any medication uses in past 8 weeks (apart from paracetamol, aspirin, local treatments, contraceptives, HRT)	Phone screen and reassessed in lab day	Not eligible
Drug/food allergies	Severe allergies	Phone screen	Not eligible
Epilepsy	Diagnosis of epilepsy History or seizures	Phone screen	Any = not eligible
Participation in another trial	Current participation in a medical trial. Recent completion of a medical trial	Phone screen	Not eligible
Registration at GP	Not registered	Phone screen	Not eligible
Acute illness	Acute illness in the past 7 days	Lab day	Not eligible
COVID-19	Having suffered from COVID-19 in the last month Having suffered from long COVID-19	Phone screen and reassessed in lab day	Not eligible

Appendix B Demographics Table: Before and After COVID-19 (Chapter 2)

Table 20

Descriptive Statistics of the Group Characteristics Before and After COVID-19

	Before COVID-19			After COVID-19		
	n	M	*SD*	n	M	*SD*
Gender	39			54		
…Female	28	72%		26	48%	
…Male	11	28%		28	52%	
Age	39	20.03	2.16	54	24.24	4.12
Ethnicity	39			54		
…White	28	72%		33	61%	
…Black	1	3%		0	0%	
…Asian	4	10%		17	31%	
…Mixed	0	0%		1	2%	
…Other	6	15%		3	6%	
Body Mass Index (BMI)	39	22.33	2.83	54	22.79	2.41
Gas Expectancy (Proportion Correct)	39			54		
…True	31	79%		44	81%	
…False	8	21%		10	19%	
GAD-7	39	3.08	2.63	54	2.44	3.23
SPIN	39	11.74	10.56	54	10.15	9.07
LSAS	39	27.23	17.01	54	25.28	20.41
PRCA-24	39	19.08	4.43	54	17.26	4.20

Note. GAD-7 (Generalised Anxiety Disorder Assessment), SPIN (The Social Phobia Inventory), LSAS (Liebowitz Social Anxiety Scale), PRCA-24 (The Personal Report of Communication Apprehension).

Appendix C Modified State Anxiety Questionnaires

Table 21

Items of the Modified GAD-7 and SASCI Questionnaires

Questionnaire	Questionnaire Item	Scoring Range
GAD-7$_{Modified}$	**Feeling nervous, anxious, or on edge**	0 = Not at all 1 = A little 2 = Moderately 3 = Quite a lot 4 = Extremely
	Not being able to stop or control worrying	
	Worrying too much about different things	
	Trouble relaxing	
	Being so restless that it's hard to sit still	
	Becoming easily annoyed or irritable	
	Feeling afraid as if something awful might happen	
SASCI$_{Modified}$	*How anxious do you currently become in anticipation of or when in social/performance situations (situations where you interact with or do something in front of people?) (O)*	0 = Not at all 1 = A little 2 = Moderately 3 = Quite a lot 4 = Extremely
	How keen are you to avoid this situation? (M)	
	How much do you currently avoid social/performance situations, being the centre of attention, or talking with people? (O)	
	Are you concerned about being the centre of attention (and interacting with people)? (M)	
	How concerned are you, currently, about doing/saying something embarrassing or humiliating in front of others, or that others might think badly of you for what you do or say? (O)	
	How embarrassed are you feeling? (M)	
	Currently, how much does your anxiety about social/performance situations interfere with your ability to participate with your ability to participate in work/school or in social activities? (O)	
	How concerned are you that others are thinking badly of you? (M)	

Note. (*O)* = Original questionnaire item. (M) = Modified questionnaire item. Items in bold are included in the GAD-7$_{Modified}$ questionnaire.

Appendix D Instruction Scripts Used During In-person Experimental Protocol (Chapter 3)

Study Title: Exploring Social Interactions Using Professional 360 VR Camera Technology

Researcher: Nesli Ozhan, Dr Erich Graf, Prof Matt Garner

ERGO Ethics Approval Number: 67176 (Version 2, 19 February 2022)

UNIVERSITY OF Southampton

Hello, welcome to the second phase of the experiment.

Before we start, I would like you to fill in the questions which should be on the laptop screen. The survey will tell you when to stop.

--- BASELINE MEASURES----

During the final math portion of the experiment, you will be asked to complete some maths calculations.

You will verbally report your answers aloud and be asked to start over if a mistake is made.

This session will be audio and video recorded. **Show the audio and video recorder to the participant.* *

Before we start, could you please proceed on the survey by pressing the blue arrow? The survey will tell you when to stop so that we can proceed with the calculations.

----PRE-MEASURES----

**Participant tells you that they are ready.*

Okay, we can start now. Please answer as fast and as accurate as possible. **If the participant makes a mistake, prompt them with: "That is incorrect, please start over from XXX."* *

3 times incorrect answer = skip to the next question.

15 second maximum per question before moving on.

10 – 5 = 5 (Ten Minus Five)

25 + 8 = 33 (Twenty-Five Plus Eight)

31 X 10 = 310 (Thirty-One Multiplied by Ten)

151 – 62 = 89 (One Hundred and Fifty-One Subtracted by Sixty-Two)

1058 – 58 =1000 (One Thousand and Fifty-Eight Minus Fifty-Eight)

23 – 1042 = - 1019 (Twenty-Three Subtracted by One Thousand Forty Two)

15 x 15 = 225 (Fifteen Multiplied by Fifteen)

320 / 4 =80 (Three Hundred Twenty Divided by Four)

This is the end, thank you. Could you please proceed on the survey by pressing the blue arrow for the last time?

---POST MEASURES---

Experiment completed – Experimenters can now behave normal.

Appendix E Supplementary Analysis for the Habituation Hypothesis (Chapter 3)

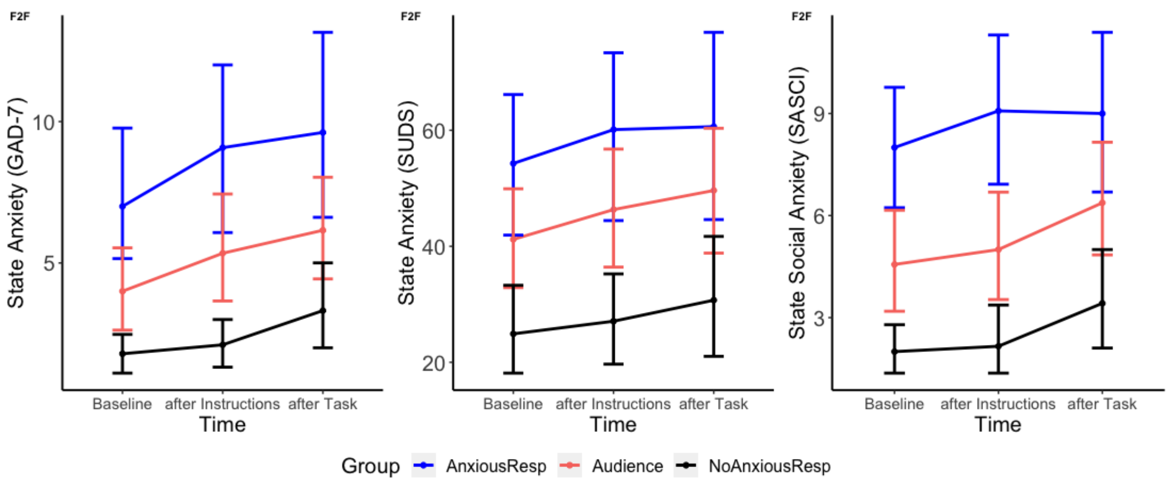
We broke down the control group (No Audience) into those who did and did not have an anxious response to the empty virtual room (Anxious Response Control versus Non-Anxious Response Control). We identified the median value of self-reported social anxiety scores ($SASCI_{Modified}$, M = 3.99) as our cut-off. We ended up with three levels for the factor 'Group' (Audience, n = 32; Anxious Response Control, n = 13; Non-Anxious Response Control, n = 19).

We then conducted a 3 (Group: Audience, Anxious Response Control, Non-Anxious Response Control) x 3 (Time: Baseline, *after* Instructions, *after* Task) linear mixed-effects model on state anxiety ($GAD\text{-}7_{Modified}$, SUDS) and state social anxiety ($SASCI_{Modified}$) to investigate the influence of the photorealistic VR exposure on the subsequent *in-person* socially evaluative task on state anxiety levels. No interaction effects reached significance (Fs <0.95, ps > .430, η2ps <.030). However, upon examining Figure 25, it seems that participants who were in the control group (No Audience) but recategorized based on the anxious arousal during their talk in VR exhibited numerically distinct baseline anxious reactions, although the patterns were similar across groups.

Although our Group levels were randomised, because we did not implement screening to recruit subclinical/clinical socially anxious populations, this finding might underscore the importance of trait characteristics (i.e., fear of public speaking, social anxiety) in testing habituation processes within such a design, which eventually could provide valuable therapeutic insights.

Figure 25

Interaction Plots: Self-reported State Anxiety ($GAD\text{-}7_{Modified}$, SUDS, $SASCI_{Modified}$) During Face-to-Face Tasks by Group (Refactored)



Note. Error bars represent 95% CIs (confidence intervals, bootstrapped). F2F = The face-to-face phase.

Appendix F Instruction Scripts Used During the Online Videoconferencing Session (Chapter 4)

[Welcoming]

[Share Files-Slide1]

Hello XXX. Welcome to today's event. Can you hear me well? I am Nesli, the moderator of this event. I assume you have read the participant information sheet and roughly have an idea about what is going to happen, right? If not, I am more than happy to explain the protocol again.

[Ask participants to turn on the video if it is not already on.] *Before starting, would you be able to turn on your video? There should be a symbol button at the middle bottom of your screen for you to do that.*

[Share Files- Slide 2]

Thank you. Okay, now, I would like to take a moment to make you familiar with the videoconferencing environment. Let's start with the interface [use the pen here]. **[STOP SLIDE 2 SHARING].** *This is what the general interface looks like. Here each square is representing one of our audience attending today's talk and on the left bottom of your screen, you will see how your video is streamed to the audience. Can you see that? Great…* [Share Files Slide 2 - again] *At the middle bottom of your screen [use the pen here], there are options for you to turn on/off your video and mute or unmute your audio. Please do not change the settings we have started with. I might sometimes control these to allow for a smooth presentation. You should also be seeing a purple arrow [use the pen here] on the right bottom of your screen. Are you able to see it? If you click on that arrow NOW, you will have access to the chat panel in case you might receive some messages from the audience. You might want to leave that chat panel on during the session so that you will have immediate access to chat messages from our audience. If you click on the people symbol next to the chat bubble, you can also view all the attendees. Today we are expecting to have around 20 attendees. Our audience is from the University of Southampton staff and students. As you may have realised they have already started populating the room and by the time you are ready, they all should be here. You will not need to use the next two tabs so do not worry about these. One final thing, this session is going to be recorded[use the pen here] . Is it okay for you? Okay, then I am starting to record.* **[START RECORDING]**

[STOP Sharing Files - SLIDE 2].

[beforePrep]

Okay, now you will need to prepare your talk. You will shortly see the topic with some prompts so that you can shape your talk on. You will have three minutes for preparation and there will be a countdown timer available on your screen too. Before sharing your topic, there will be some questions shared on the screen for you to answer. To indicate your answer, you can use the chat box and reply where I just sent you a message. **---------SEND TEXT NOW---------- You can type in your answers here. This is a private chat. The conversation is only visible to you and me.** Have you received it? *This particular chat is private, meaning that it can be seen by only you and me. There will be more than one question shared on the screen, and each time your answer to a question appears on the chat; you will then see the next question. After you answer all questions, I will share your topic so that you are able to start preparing your talk. Is everything clear? Then, let's start with the first question. Okay?*

---------SHARE Files, SLIDE 3, 4, 5, 6, 7, 8, 9, 10, 11----------

------------STOP SHARING SCREEN---------- (PCP CAN SEE THE AUDIENCE)

[Prep]

Thank you for your answers. Now I am sharing the topic on the screen for you to prepare your talk. Aaaand… Here you go. **---------SHARE Application - TOPIC SCREEN------------**

--*You now have three minutes to prepare. At some point during your prep, you will see some questions on the screen and be asked to answer those. Again, I will direct you to the private chat so that you can type in your answers. Is it okay? Are you ready? Okay, your time starts now.*

1.5 mins ---> **---------SHARE SLIDE 3, 4, 5, 6, 7, 8, 9, 10, 11----------**

----------------------RE-SHARE Application - TOPIC SCREEN------------------

1.5 mins more for prep - ADD 10 more dummy audience

[beforeTalk] - ADD 5 more dummy audience

Okay, your time is now over. **[STOP Sharing Files – SLIDE].** Great. Looking at the attendees' list, I can see that our audience is all here too. Hello everyone and thank you for attending this talk. Today we have XXX as a speaker.

Dummy audience 1: Hello! Dummy audience 2: Hi everyone

XXX is going to give us a talk on artificial intelligence and its harms and benefits. Juuust in a few minutes. Well XXX, before your talk, the screen will show you some questions again and you can type in your answers to our private chat. I have sent another text there now so it should now pop up. **---------SEND TEXT NOW---------- You can type in your answers here. This is a private chat. The conversation is only visible to you and me.** After answering all questions, I will tell you to start delivering your speech to our audience.

---------SHARE SLIDE 3, 4, 5, 6, 7, 8, 9, 10, 11---------- Thank you for your answers. **----------STOP SCREEN SHARING-----------**

[Talk]

You should aim for a three-minute talk. I will tell you when your time is over. You can start now.

[afterTalk 1]

Thank you for your talk. And thank you all for attending today’s talk. This was the end of today's session. I hope you’ve enjoyed.

Dummy audience 1: Thank you! Dummy audience 2: Thanks, bye everyone. Dummy audience leaves the session.

XXX, for the last time, you will see some questions. Again, can you type in your answers to the private chat. I have sent another private text to you now. Each time your answer appears on the chat, you will see the next question. **---------SEND TEXT NOW---------- You can type in your answers here. This is a private chat. The conversation is only visible to you and me.**

---------SHARE SLIDE 3, 4, 5, 6, 7, 8, 9, 10, 11----------

----------STOP SCREEN SHARING-----------

[afterTalk 2]

Thank you for your answers. This is the end of the videoconferencing session. As the final stage, I am sharing this survey link with you. It contains some questions regarding this event and will take approximately 10 minutes to complete. **-----SHARE SURVEY LINK----** Please now click on the survey link. Does it look okay? Make sure you fully complete and then submit your answers so that your time can be fully compensated. Thank you for joining us today. You may now leave this chat by closing this web browser and start completing the survey link. I will receive a confirmation email once you complete it and your time will be compensated. Bye.

Appendix G Supplementary Analysis (Chapter 4)

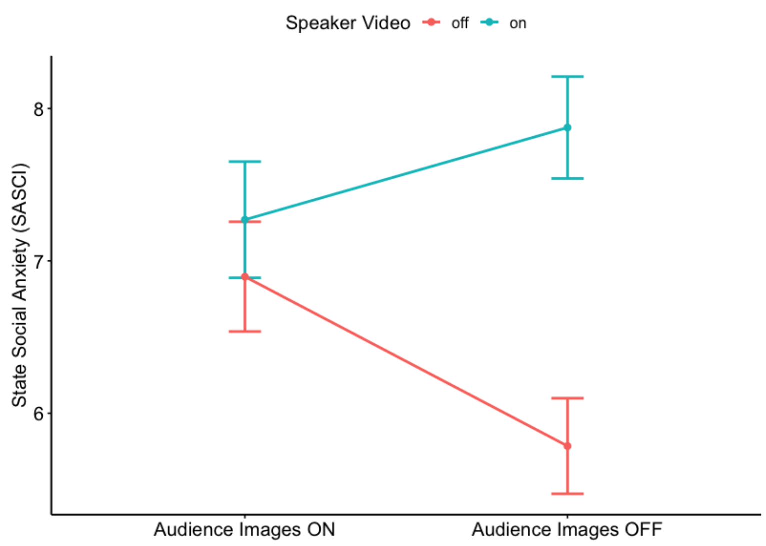
We verified our analyses with Welch's ADF package in R (Villacorta, 2017), due to slight residual non-normal distributions and violation of sphericity (for repeated measures). Welch-James approach protects against non-normality using approximate degrees of freedom and trimmed means, and against Type I error through bootstrapping (Wilcox, 2011). However, the cell sizes for the smallest number of subjects, especially when involving a repeated measures variable, is recommended to be at least four or five times greater than the number of repeated measures, and this proportion increases when interactions are involved (Villacorta, 2017). Given that our design might not fully meet this criterion due to our sample size at group level ranging from 29 to 32, we decided not to report this result in the main text. What follows now is the different findings between the statistical tests that we reported in the main text and the Welch-*F* tests for the $SASCI_{Modified}$.

SASCI Analysis using Welch-James Approach

Different than the results reported in the main text, the robust test revealed a main effect of Self, $WJ_{1,378.2}$ = 9.61, *p* =.002, and a significant interaction of Speaker*Audience, $WJ_{1,378.2}$ = 5.65, *p* =.017. As in Figure 26, a simple main effects analyses revealed that when dummy audience pictures were available, having the web camera on or off did not influence anxiety levels, *F*(1, 117) = 0.123, *p* = .726. However, if dummy audience images were not available, participants felt higher social anxiety when their web camera was on relative to it being off, *F*(1, 117) = 4.19, *p* = .042, although this effect was marginal.

Figure 26

*The Interaction Effect of Audience*Speaker for State Social Anxiety*



Note. Higher scores denote worse social anxiety scores. Error bars represent standard error (SE).

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