Investigating the Feasibility & Design of Virtual Reality Exposure Therapy for Subclinical Anxiety

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A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

22nd June 2026

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ABSTRACT

This thesis explores the feasibility, acceptability, and design considerations for Virtual Reality Exposure-Based Therapy (VRET) for adults with subclinical anxiety. Although subclinical populations are at increased risk for developing full-threshold disorders, they remains underrepresented in both research and treatment. VRET is a promising intervention for anxiety-related conditions, but its use for subclinical cases, and specifically for subclinical contamination Obsessive-Compulsive Disorder (OCD) and fear of needles, has not been sufficiently investigated.

Contamination OCD and fear of needles were selected as use cases due to their significant public health implications, including functional impairment and healthcare avoidance. These conditions also reflect distinct yet complementary anxiety profiles: contamination OCD involves obsessional thoughts and compulsive behaviors, while fear of needles is characterized by specific phobic avoidance. Both are well-established targets for exposure-based therapy and involve visual/situational triggers that are particularly well-suited to simulation in virtual environments. Studying both conditions offered early insight into whether VRET could be applicable across differing forms of anxiety symptomatology.

The thesis includes five studies. A systematic review highlights gaps in the existing anxiety VRET literature. A survey study characterizes the associated symptom profiles and life interference. Two case studies conduct early-phase feasibility evaluation of VRET for these two conditions. A final study analyzes physiological data to identify markers of anxiety and explore whether machine learning models can distinguish between different anxiety profiles during virtual exposures.

Together, these studies demonstrate that VRET can evoke anxiety responses suitable for exposure-based interventions in these two subclinical anxiety cases. The findings suggest that VRET is an acceptable and promising option for individuals who may not access traditional therapy. By focusing on subclinical anxiety and leveraging scalable digital tools, this research supports the development of more accessible, preventative mental health interventions and advances efforts to democratize care for populations traditionally underserved by conventional therapeutic models.

ACKNOWLEDGEMENTS

A great many people have supported me throughout my PhD program. Without their help, this project might never have gotten off the ground, and the process would have been a great deal less enjoyable (and certainly much more chaotic). I am especially grateful to my primary supervisor, Dr. Nejra van Zalk, whose unwavering support through many, many drafts and expert guidance have profoundly shaped me as a researcher. Thank you for taking a chance on me and for nurturing not just this project, but also my confidence, curiosity, and growth as a scientist. Your example has taught me the value of combining intellectual rigor with openness and creativity, a balance I will strive to bring to all my future work. I would also like to thank Dr. Martina Di Simplicio, my secondary supervisor. Your guidance through the many stages of the PhD journey has been invaluable. Your thoughtful feedback and encouragement helped me stay focused and maintain sight of the broader clinical context.

A huge thank you to Dr. Jacqueline Nesi and Dr. Taylor Burke for taking me under your wing and both being incredibly generous with your time. Jackie, your mentorship has been a model of generosity and care, and I have learned from you not only about research but also about leading with empathy and perspective. Taylor, your insight and encouragement have been matched only by your example of how to approach psychology in a way that is both deliberate and rigorous, while still maintaining a sense of balance beyond the day-to-day work. I am also grateful to the wonderful friends, collaborators, and colleagues I have had the pleasure of working with at The Design Psychology Lab and beyond: Jianan Zhou, Ian Chard, Adile Dicle Akin, Dr. Talya Porat, Dr. Aniruddha Voruganti, Dr. Georgina Krebs, and Ruksana Shaukat-Jali. It has been an honor to learn from each and every one of you.

This project would not have been possible without those who participated in our studies. I am deeply grateful for your time, openness, and enthusiasm. You strengthened my passion for this work and renewed my motivation to contribute meaningfully to the field. An additional thank you to the London Interdisciplinary Social Science Doctoral Training Partnership and XRHealth, whose generous support provided both the resources and the opportunities that made this research possible. Your contributions not only enabled the practical side of this work, but also encouraged its ambition and scope.

Finally, my deepest thanks go to my parents, whose steadfast love, support, and enthusiasm for my (admittedly long) educational journey have meant more than I can say. Thank you for always being there for me and for reminding me that enjoying the path is the whole point. I promise there will be a job at the end of it... after just a *little* more education.

I am also immensely grateful to Elliot, who not only wrangled my LaTeX and machine learning code into submission, but also kept me well-fed through the process. Your help, care, and good humor have been a constant anchor. I am so excited for our next chapter together, taking on all the adventures that await us as we make New York City our new home.

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List of Acronyms

AI	artificial intelligence
AR	augmented reality
CAVE	cave automatic virtual environment
CBT	cognitive-behavioral therapy
CMS	Centers for Medicare & Medicaid Services
EDA	electrodermal activity
ERP	Exposure and Response Prevention
FDA	Food and Drug Administration
HCD	human-centered design
HMD	head-mounted display
HR	heart rate
KNN	K-Nearest Neighbors
LISS-DTP	London Interdisciplinary Social Science Doctoral Training Partnership
MFS	Medical Fears Survey
MICE	Multiple Imputations with Chained Equations
ML	machine learning
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NIHR	National Institute for Health and Care Research
OCD	Obsessive-Compulsive Disorder
OCI-R	Obsessive Compulsive Inventory-Revised
PANAS	Positive and Negative Affect Schedule
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROMIS anxiety	Patient Reported Outcomes Measurement Information System - Anxiety
PTSD	Post-Traumatic Stress Disorder
QATSDD	Quality Assessment Tool for Studies with Diverse Designs
SPQ	Specific Phobia Questionnaire
SSQ	Simulator Sickness Questionnaire
SSRIs	Selective Serotonin Reuptake Inhibitors
SUDS	Subjective Units of Distress Scale
SUS	System Usability Scale

SVM	Support Vector Machine
VR	virtual reality
VRET	Virtual Reality Exposure-Based Therapy

1 | Introduction

> *"Expose yourself to your deepest fear; after that, fear has no power, and the fear of freedom shrinks and vanishes. You are free."*
>
> Jim Morrison

Our capacity for fear and anxiety has evolved to protect us by steering us away from danger. But when these systems overfire, they can hold us back, leading to avoidance, distress, and impairment. Evolutionary psychology suggests that such overactivation is not a flaw but a feature. Anxiety systems are tuned to overreact, because the cost of missing a real threat is often much greater than the cost of a false alarm (Nesse, 2001).

Psychological therapies help individuals recognize these alarms and respond to them more effectively. Exposure therapy, in particular, provides a structured method for engaging with feared stimuli in ways that build tolerance and reduce avoidance. With advances in technology, this process no longer has to take place in physical settings alone.

VRET allows individuals with anxiety-related symptoms to encounter and respond to their fears in immersive, simulated environments that offer both control and realism. This thesis conducts early-phase evaluation of VRET as an acceptable and potentially effective tool for reducing anxiety in subclinical populations, whose symptoms cause meaningful distress and impairment but do not meet formal diagnostic criteria. Although VRET is increasingly used in clinical contexts for diagnosed disorders, its application to subclinical cases remains underexplored. By focusing on this underserved group, the project examines whether VRET can help fill the treatment gap, particularly in situations where traditional therapy may be inaccessible, unavailable, or declined.

To explore this, the thesis examines two distinct but complementary conditions: subclinical contamination-featured OCD and fear of needles. These conditions were selected because they respond well to exposure-based therapy and involve visual or situational triggers that are well-suited to virtual simulation. Importantly, they also reflect different anxiety profiles. Contamination OCD (Case Study I) involves obsessive thoughts and compulsive behaviors, while fear of needles (Case Study II) involves phobic avoidance of specific stimuli. Studying both allows the project to assess whether the benefits of VRET generalize across different anxiety profiles.

The remainder of this chapter provides background on anxiety-related disorders and the importance of addressing subclinical symptoms. It then introduces the theoretical and clinical foundations of exposure-based therapy, followed by an in-depth discussion of VRET as a digital tool for overcoming key treatment barriers. Throughout, the focus remains on whether VRET can be a potentially effective and acceptable intervention for subclinical anxiety populations, as demonstrated through the two selected case studies.

1.1 Anxiety-Related Disorders

Globally, an estimated 301.4 million people are affected by at least one anxiety-related disorder, a number that continues to rise alongside population growth and again in most countries (Javaid et al., 2023). Indeed, anxiety-related disorders are one of the most internationally prevalent psychological conditions (Kieling et al., 2024; McGrath et al., 2023; Steel et al., 2014). These anxiety-related disorders span specific phobias, OCD, and General Anxiety Disorder, amongst many more. Among all ages, the prevalence of anxiety-related disorders is higher in women than in men (Javaid et al., 2023; McGrath et al., 2023). Prevalence is also reported to be higher in high-income countries in North America and Europe, and has been found to be strongly correlated with economic development (Javaid et al., 2023).

The experience of anxiety can involve an increased heart rate, an increase in electrodermal activity (EDA) (i.e., sweating), and an increase in skin temperature (i.e., flushed skin), as well as racing thoughts (e.g., Nikolić et al., 2018). These physiological responses are believed to reflect an evolutionary fight-or-flight mechanism, preparing the body to confront or escape perceived threats (Cannon, 1914). The physiological arousal that occurs is due to the activation of the parasympathetic and/or sympathetic autonomic nervous system (Berntson et al., 1994). Increase in EDA is an indicator of sympathetic nervous system activation, while increase in heart rate is an indicator of both sympathetic activation and parasympathetic deactivation (Kreibig, 2010; Nikolić et al., 2018). The psychological experience of anxiety is often assessed using standardized questionnaires, such as the Patient-Reported Outcomes Measurement Information System–Anxiety (Pilkonis et al., 2011), Beck Anxiety Inventory (Beck et al., 1988), and Subjective Units of Distress Scale (Wolpe, 2018). Integrating physiological measures with traditional psychometric assessments within a multimodal framework reflects the principles of current transdiagnostic and dimensional approaches in psychological research (Cuthbert, 2015; Eaton et al., 2023; Kotov et al., 2022). To better understand the complex fingerprint of anxiety, research on both subjective and physiological markers of anxiety is necessary.

This multidimensional approach is particularly important given the high rates of comorbidity and sequential comorbidity (i.e., co-occurrence and development in succession) among anxiety-related disorders, which suggest shared underlying mechanisms and overlapping symptom profiles (Haller et al., 2014; Ströhle et al., 2018). The frequent comorbidity and recurrence of anxiety-related disorders not only complicate diagnosis and treatment, but also contribute to their high prevalence and persistence across the lifespan (Javaid et al., 2023; X. Yang et al., 2021). These factors collectively make anxiety disorders one of the leading contributors to global disability, with wide-ranging economic costs and significant strain on healthcare systems (Javaid et al., 2023; Kieling et al., 2024; McGrath et al., 2023; Steel et al., 2014). Anxiety-related disorders are associated with significant increase in individual health care costs and are recognized as a public health issue (Konnopka & König, 2020; Zayat & Hoskins, 2025). In 2022-2023 alone, the NHS Talking Therapies program in England received 1.76 million referrals for treatment of anxiety and/or depression, reflecting the substantial demand for

mental health services and the associated burden on the healthcare system ('NHS Talking Therapies, for anxiety and depression, Annual reports, 2022-23', 2024).

Subthreshold anxiety disorders are estimated to affect between approximately 6% and 11% of the general adult population, with some disorder-specific estimates considerably higher (Haller et al., 2014; Zhong et al., 2024). Critically, individuals with subthreshold anxiety are more than twice as likely to develop a full threshold anxiety disorder compared to those without subthreshold symptoms (Zhong et al., 2024). Despite this, subclinical cases often go untreated, representing a critical but overlooked segment of the mental health burden. This thesis addresses that gap by focusing on subclinical anxiety and the potential of VRET as a scalable intervention.

1.2 Subclinical Symptoms

Anxiety-related disorders are experienced on a full spectrum of symptomatology and everyday life interference (Korte & Schmidt, 2020). However, not all individuals experiencing anxiety symptoms receive a formal diagnosis. This may be due to a variety of factors, including personal barriers such as mental health illiteracy, stigma, or skepticism about treatment, as well as systemic barriers like limited access to clinicians and long wait times (Conroy et al., 2020; Long et al., 2023; Waumans et al., 2022). Additionally, some individuals may not meet the full diagnostic criteria in terms of symptom severity, frequency, or functional impairment, and are therefore unable to receive a diagnosis.

It is important to distinguish between diagnosed, clinical, and subclinical presentations of anxiety. Individuals with diagnosed anxiety both meet clinical thresholds and have received a formal diagnosis from a healthcare professional. By contrast, clinical individuals meet diagnostic criteria, but have not received a formal diagnosis. There is a lack of consensus on the exact definition of subclinical anxiety, but for the purposes of this thesis, subclinical anxiety is defined as the experience of anxiety symptoms that do not meet full diagnostic criteria and, therefore, are not eligible for a formal diagnosis (Rivas-Vazquez et al., 2004; Witlox et al., 2021). Despite falling below the diagnostic threshold, subclinical anxiety is not benign; it is associated with functional impairment and increased risk for developing full-threshold anxiety or other mental health conditions over time (Karsten et al., 2013).

Increasingly, transdiagnostic dimensional models, network approaches, and clinical staging frameworks are being utilized to address the limitations of traditional categorical or dichotomous approaches to psychopathology (Eaton et al., 2023). Transdiagnostic dimensional approaches aim to address several key limitations of traditional diagnostic systems, including high comorbidity among anxiety-related disorders, arbitrary diagnostic thresholds, overlapping criteria across disorders, and the inability to capture heterogeneity within a single diagnosis (Eaton et al., 2023). With this view, the whole continuum of symptoms,including undiagnosed subclinical symptoms, is of research and clinical value.

Subclinical anxiety symptoms can manifest across a range of presentations, including subthreshold generalized anxiety, social anxiety, specific phobias, panic, and agoraphobia (Zhong et al., 2024). While all of these warrant research at-

tention, not all are equally suited to VRET as a delivery modality, nor equally underrepresented in the existing literature. Despite growing evidence of their clinical significance, subclinical populations remain understudied and undertreated (Angst et al., 1997; Bjelland et al., 2009; Witlox et al., 2021). To begin addressing this gap, this thesis focuses on two specific anxiety-related use cases: subclinical contamination-featured OCD and subclinical fear of needles. The selection of these two conditions was motivated by several converging considerations. Both are prevalent in subclinical forms in the general population, as documented in Chapter 3, and carry significant public health consequences, including healthcare avoidance and, in the case of fear of needles, reduced vaccine uptake. Both are well-established targets for exposure-based therapy, providing a shared treatment mechanism that enables meaningful comparison across the two cases. Importantly, they represent mechanistically distinct anxiety profiles: contamination OCD involves obsessional thinking and compulsive responding, associated with sympathetic hyperactivation, whereas fear of needles involves specific phobic avoidance and is more commonly associated with vasovagal responses. Studying both conditions therefore tests whether VRET can generalize across meaningfully different anxiety types. At the same time, both share key experiential features, notably anticipatory threat processing and avoidance behavior, that make them theoretically comparable within an exposure-based framework, as explored in Chapter 6. Both conditions are also underrepresented in the existing VRET literature relative to conditions such as acrophobia and social anxiety, as confirmed by the systematic review in Chapter 2. Finally, both had clinically deployed virtual reality (VR) environments available through an industry partner, enabling evaluation of tools already in active clinical use but not yet empirically tested. Throughout this thesis, these cases are referred to as Case Study I (OCD) and Case Study II (fear of needles).

Studying two distinct conditions necessarily limits the depth of investigation possible for each, particularly with respect to session variety, sample size, and follow-up duration. However, for early-phase feasibility evaluation, breadth across mechanistically distinct anxiety presentations is more informative than depth within a single condition, as it provides preliminary evidence of generalizability that can direct and prioritize more focused future research.

1.3 Case Study I: Subclinical Obsessive-Compulsive Disorder

OCD is defined by the presence of recurrent, intrusive thoughts, images, or impulses that elicit marked distress. These obsessions typically result in the performance of compulsive behaviors or mental rituals, which are intended to neutralize the anxiety or prevent feared outcomes (Rasmussen & Eisen, 1992). OCD is the fourth most prevalent psychiatric conditions and is associated with substantial functional impairment, reduced quality of life, and significant socioeconomic consequences, including occupational dysfunction and income loss (Kochar et al., 2023; Veale & Roberts, 2014). Epidemiological data from the National Comorbidity Survey Replication indicate a lifetime prevalence of approximately 2.3% (Kessler et al., 2012), although this is likely an underestimation due to underreporting related to stigma and lack of symptom recognition (Brady et al., 2010).

The present thesis focuses specifically on subclinical contamination-featured OCD symptoms, that is, individuals who experience clinically meaningful obsessional and compulsive symptoms but do not meet full diagnostic criteria.

The contamination/washing symptom dimension is the most frequently endorsed among individuals with OCD, with approximately 50% reporting contamination-related OCD symptoms (Rasmussen & Eisen, 1992). Contamination-featured OCD symptoms in particular can negatively affect relationships, ability to study or work, prevent accessing medical services, and lead to related health consequences, such as dermatitis due to excessive hand-washing (Veale & Roberts, 2014). It can also lead to avoidance of socialization and inability to live independently (Veale & Roberts, 2014).

From a theoretical perspective, contamination-related OCD symptoms are often linked to heightened disgust sensitivity, overestimation of threat, and inflated responsibility (Olatunji, Sawchuk et al., 2005). These cognitive distortions contribute to the development and persistence of intrusive thoughts and compulsive behaviors. The cognitive-behavioral model of OCD emphasizes how individuals misinterpret intrusive thoughts (e.g., thoughts about dirt, germs, or illness) as dangerous, morally unacceptable, or personally significant (Taylor et al., 2007). These misinterpretations can trigger compulsions like excessive hand washing or cleaning rituals, which temporarily reduce distress but reinforce dysfunctional beliefs over time. Exposure and Response Prevention (Exposure and Response Prevention (ERP)), the gold-standard cognitive-behavioral treatment for OCD, aims to disrupt this cycle by systematically exposing individuals to contamination-related fears while preventing the compulsive responses that maintain them ('Clinical Guideline 31', 2005). Meta-analytic evidence indicates that cognitive-behavioral therapy (CBT) incorporating ERP produces large effects on OCD symptom reduction relative to control conditions, with effects maintained at follow-up (Olatunji et al., 2015). The theoretical and clinical foundations of exposure-based therapy are discussed in further detail in Section 1.5.

The cost-of-illness of diagnosed OCD in the UK, encompassing its societal impact (e.g., lost productivity, out-of-pocket expenditure, and private therapy), is estimated to be over £5 billion annually or over £7,000 per person on average, irrespective of treatment (Kochar et al., 2023). It is notable that the societal cost accounts for the vast majority (92.3%) of the total cost-of-illness (Kochar et al., 2023; Veale & Roberts, 2014). Importantly, this estimate excludes individuals with subclinical symptoms, suggesting that the true economic, public health, and social impact may be substantially higher.

In light of this, it is crucial to develop effective interventions that are accessible, have low refusal rates, can be tailored to an individual's specific OCD symptoms, and do not require a formal diagnosis for eligibility.

1.4 Case Study II: Fear of Needles & Injections

Fear of needles (also known as needle phobia or trypanophobia) is a condition that involves strong anxiety about medical procedures that use needles or injections. It often leads to physical symptoms such as an increased heart rate, a sudden drop in blood pressure that may result in fainting, or feelings of panic when

seeing needles (McLenon & Rogers, 2019). It is often studied under the umbrella of blood-injection-injury phobia, but individuals who fear needles and injections do not necessarily have a fear of blood.

Fear of needles is a common condition, with prevalence estimates between 20% and 30% in the general adult population, and higher rates observed among younger individuals and females (McLenon & Rogers, 2019). The prevalence is even greater in individuals with chronic medical conditions, particularly diabetes (0.2% to 80%), cancer (17% to 52%), and chronic kidney disease (25% to 47%) (Duncanson et al., 2021). Avoidance behaviors associated with fear of needles can interfere with essential medical care, including vaccine uptake, routine procedures, and blood donation, potentially leading to poorer health outcomes (Alsbrooks & Hoerauf, 2022; McMurtry et al., 2015). It has been documented that of individuals reporting a fear of needles, up to 52.2% have avoided blood draws, 49.0% have avoided blood donations, and 33.1% have avoided vaccinations (Alsbrooks & Hoerauf, 2022).

Despite its impact on health behaviors, it is rarely formally diagnosed or addressed in clinical practice (Bienvenu & Eaton, 1998). A major contributing factor is avoidance behavior; by avoiding medical settings where needles are present, individuals also avoid opportunities for their fear of needles to be identified and treated. This pattern of avoidance and underdiagnosis likely also contributes to the scarcity of research on effective interventions (Love & Love, 2021).

Evidence-based treatment options are limited, particularly for adults. Commonly used interventions include applied tension to prevent vasovagal syncope and breathing techniques to manage acute anxiety responses (McLenon & Rogers, 2019). However, these approaches primarily address physiological symptoms and do not target the underlying fear or avoidance. Exposure-based therapy remains the most effective intervention for addressing the core components of the phobia. Current evidence suggests that applied tension does not provide additional benefit when combined with exposure therapy (Ayala et al., 2009). The substantial public health, economic, and social burdens associated with fear of needles highlight the urgent need for expanded research and the development of scalable, evidence-based interventions.

To my knowledge, there has not yet been a study quantifying the cost-of-illness of fear of needles. However, there is substantial evidence that fear of needles affects both individual health outcomes (e.g., worse health due to delaying medical care) and societal health (e.g., decreased herd immunity or increased risk of disease outbreak due to reduced vaccine uptake) (Alsbrooks & Hoerauf, 2022; Love & Love, 2021; McMurtry et al., 2015; Taddio et al., 2012, 2022). These public health consequences also lead to economic burden, as avoidance of preventative care leads to increased health care costs over time (McMurtry et al., 2015). Consequently, there is a clear rationale for developing targeted interventions. Given that fear of needles is prevalent, variable in symptom severity, and differs in the degree of functional impairment, it is appropriate to prioritize treatment approaches that are broadly accessible without diagnosis and demonstrate low rates of refusal, similar to strategies needed to treat OCD.

1.5 Traditional Treatment

The traditional first-line gold-standard treatments for OCD and fear of needles are exposure-based (Steinman et al., 2016). For OCD, the traditional first-line treatment is CBT often in the form of Exposure and Response Prevention ('Clinical Guideline 31', 2005), and exposure is a key active ingredient of this. For specific phobias, of which fear of needles is one, exposure is also considered the first-line treatment (Norton & Price, 2007).

Selective Serotonin Reuptake Inhibitors (SSRIs) are considered first-line pharmacological interventions for OCD and have been found to be significantly more effective compared to placebo, though effect sizes are generally small (Fineberg et al., 2012; Kotapati et al., 2019). Approximately 40% of individuals with OCD do not respond to SSRIs, and only a minority achieve full remission, with outcomes varying depending on the specific SSRI used (Denys, 2006; Goljevscek & Carvalho, 2011). Although SSRIs combined with CBT can enhance outcomes, evidence suggests the combination offers no substantial benefit over CBT alone (Kotapati et al., 2019). Tricyclic clomipramine and SSRI augmentation with low-dose neuroleptic medication, such as risperidone, have been successfully used for individuals who do not respond to SSRIs, but side effects and lack of consistent success relegate them to second-line interventions (Pittenger & Bloch, 2014). In studies comparing CBT, clomipramine, and a combination of CBT and clomipramine, as well as CBT with SSRIs and CBT with risperidone, CBT was found to be dramatically more effective with combination treatments offering no additional improvement (Foa et al., 2005; Pittenger & Bloch, 2014; Simpson et al., 2013).

No pharmacological intervention has been proven to be reliably successful in the treatment of specific phobias (Choy et al., 2007). As with many other anxiety-related disorders, prescription of benzodiazepines is the most common pharmacological intervention. However, it has demonstrated little benefit and, in some cases, has been seen to worsen specific phobia symptoms over time (Thom et al., 2000; Wilhelm & Roth, 1997). Meta-analytic evidence indicates that exposure-based treatment produces large effects on specific phobia symptom reduction relative to waitlist controls, with effect sizes against placebo increasing from post-treatment to follow-up (Wolitzky-Taylor et al., 2008). This strong evidence underscores the need to understand the mechanisms through which exposure therapy achieves its therapeutic outcomes.

1.6 Theoretical Background of Exposure

Exposure-based therapy involves confronting a fear-provoking stimulus in a controlled environment, enabling anxiety habituation and/or belief disconfirmation (Craske et al., 2012, 2014; 'What Is Exposure Therapy?', 2017). Its effectiveness as an intervention for fear and anxiety has been well-documented (e.g., Norton and Price, 2007). Traditionally, the two methods of conducting exposure are in vivo (i.e., the individual is asked to confront their anxiety stimulus in real-life) or imaginal (i.e., the individual is asked to imagine their anxiety stimulus). Though both in vivo and imaginal exposure techniques have been found effective, there

seems to be a slight further improvement at follow-up when using in vivo techniques (Foa et al., 1985; Teunisse et al., 2022). Exposure can also be conducted as flooding versus gradual exposure. Flooding is when the individual is immediately exposed to their most feared stimuli in an intense regimen, whereas gradual (also called graded) exposure often involves the creation of an exposure hierarchy to identify and begin with less anxiety-inducing situations that gradually progress into more challenging exposures (Moulds & Nixon, 2006). Although flooding can yield promising outcomes, it is also associated with higher dropout rates due to the distressing and intense nature of the exposure process (Moulds & Nixon, 2006). These clinical considerations point toward the need to ground treatment in a clear understanding of the theoretical mechanisms underlying exposure therapy.

Exposure-based therapy reduces fear responses by fostering new learning that inhibits previously conditioned fear associations (Skjerdingstad, 2024). Traditionally, the habituation model suggested that repeated exposure to feared stimuli leads to a decrease in anxiety over time, as individuals become desensitized to the stimuli (Foa & Kozak, 1986; Skjerdingstad, 2024). However, more recent research emphasizes the inhibitory learning model, which theorizes that exposure works by creating new, non-threatening associations that compete with and inhibit the original fear memories, rather than erasing them (Craske et al., 2012). This model underscores the importance of expectancy violation (i.e., experiencing outcomes that dis-confirm feared expectations) as a critical component of effective exposure therapy. Strategies such as varying the contexts of exposure, removing safety behaviors, and maximizing the discrepancy between expected and actual outcomes are employed to strengthen inhibitory learning and reduce the likelihood of fear renewal (Craske et al., 2014). These approaches aim to enhance the retrieval of non-fear associations, thereby improving the durability of treatment effects.

Despite strong evidence supporting the effectiveness, safety, and acceptability of exposure-based therapy among individuals with anxiety-related disorders, it remains one of the most underutilized evidence-based interventions in routine clinical practice (Becker-Haimes et al., 2023). This is theorized to be at least in part due to low patient health literacy and branding of exposure as an intensive, undesirable intervention (Becker-Haimes et al., 2023). It is believed that these reasons may also play into patient refusal and dropout rates (Becker-Haimes et al., 2023).

In addition to attitudinal and perceptual barriers, structural obstacles also limit access to exposure-based therapy. Hurdles to receiving treatment include cost, finding a relevant clinician, and taking time off from school/work for multiple sessions (Conroy et al., 2020). Furthermore, clinician-related factors such as limited training in exposure techniques, lack of confidence, logistical limitations, and negative beliefs about exposure-based therapy contribute to its underutilization (Moses et al., 2023). Collectively, these barriers illustrate the necessity of developing new approaches to make exposure therapy more accessible.

Digital therapeutics are evidence-based therapeutic interventions delivered through qualified software programs to prevent, manage, or treat medical conditions (Hong et al., 2021). They encompass a broad spectrum of tools, including mo-

bile applications, online platforms, and immersive technologies such as VR, and are increasingly recognized as a scalable means of extending access to evidence-based care (Hong et al., 2021). VRET represents one specific application within this broader digital therapeutics landscape, leveraging immersive simulation to deliver exposure-based interventions for anxiety-related conditions.

Digital technologies have emerged as promising tools to overcome these barriers. Teletherapy increases flexibility by enabling patients to participate in treatment from their own homes, reducing the need for travel and time away from school or work, while also minimizing the stigma associated with visiting a mental health clinic in person (Comer et al., 2017; Owens et al., 2002). Additionally, it helps address regional shortages of trained clinicians by extending the reach of services to underserved areas (Comer & Barlow, 2014). Mobile applications and online platforms provide self-guided exposure exercises, making therapy more accessible to those in remote areas or with scheduling constraints (Graham et al., 2025). Expanding beyond mobile and web-based tools, VR offers a novel platform through which exposure therapy can be delivered in a highly controlled, customizable, and immersive format. Due to its ability to simulate feared stimuli in real time with high fidelity, VR is uniquely positioned to enhance traditional exposure techniques. Its growing accessibility and adaptability have made it a subject of increasing interest in both clinical practice and research.

1.7 Virtual Reality-Based Exposure Therapy

VR is an immersive technology in which a participant experiences and engages with a created virtual environment other than the external physical environment around them (Gigante, 1993). It has been successfully used to deliver therapy for various conditions such as Post-Traumatic Stress Disorder (PTSD), addiction, eating disorders, and acute and chronic pain, as well as for many anxiety-related disorders, such as General Anxiety Disorder, Social Anxiety Disorder, and numerous phobias (Maples-Keller et al., 2017).

Compared to traditional exposure-based therapy, VRET (also called VRE) has been demonstrated to be equally effective (Carl et al., 2019). More specifically, meta-analyses have suggested that VRET can be effective for various different anxiety-related disorders and not inferior to in vivo traditional exposure-based therapy (Carl et al., 2019; Powers & Emmelkamp, 2008). Symptoms, such as contamination OCD and fear of needles, are uniquely suited to VRET, due to their reliance on visual and/or situational triggers, making them ideal candidates for immersive simulation. It is hypothesized that the plausibility and sense of physical presence in the VR environment (i.e., feeling physically present and engaged in the virtual scenario) may support effective exposure, due to its potential to encourage realistic behavior in the virtual environment (Botella et al., 2017; Slater, 2009).

VRET is already being used clinically to treat anxiety disorders in various countries. Several companies, such as XRHealth and oVRcome, have developed platforms that enable healthcare providers to integrate VRET into routine care in areas such as the UK, US, Europe, Israel, New Zealand, and Australia. The clinical adoption of VRET by these companies highlights its growing role in anxi-

ety treatment, though important areas like OCD and fear of needles still lack sufficient investigation and implementation.

Prior research on VRET for anxiety-related disorders has varied considerably in protocol design. Studies have typically involved between one and eight sessions, with individual session durations ranging from approximately 15 minutes to over an hour (see Chapter 2 for a full review). Despite this variability, meta-analytic findings indicate that VRET produces large effect sizes for anxiety symptom reduction, comparable to those of traditional in vivo exposure therapy (Carl et al., 2019; Powers & Emmelkamp, 2008). These findings establish the evidence base on which the present case studies build. The case studies reported in this thesis each employ a single-session design, consistent with early-phase feasibility evaluation, and the findings are interpreted in light of this existing literature on protocol variation.

Since the introduction of commercially available head-mounted display (HMD) VR systems, only four studies have been published that involve multiple participants and utilize dedicated exposure-based protocols for OCD (Cullen, Dowling, Segrave, Carter & Yücel, 2021; Fajnerová et al., 2023; Inozu et al., 2020, 2021). Early studies on VRET for contamination OCD symptoms demonstrated that it can effectively provoke anxiety and disgust responses, as well as potentially reduce symptoms, but small sample sizes and inconsistent protocols limited their clinical relevance (Inozu et al., 2020, 2021). Later research involving diagnosed populations showed that VRET elicits anxiety responses comparable to traditional in vivo exposure and may improve engagement and task adherence, though many studies remained exploratory and lacked evidence of sustained symptom reduction (Cullen, Dowling, Segrave, Carter & Yücel, 2021). More recent work has reported promising outcomes for distress and compulsive behaviors, but questions remain regarding long-term efficacy, acceptability, and participant experience (Fajnerová et al., 2023).

VRET's use for fear of needles also remains largely unexplored. Most existing studies employ VR as a distraction tool rather than for exposure-based intervention (Aydın & Özyazıcıoğlu, 2019; Chad et al., 2018; Tanja-Dijkstra et al., 2014), and research often focuses on specific populations such as young children or individuals with Autism Spectrum Disorder, where severe avoidance may require intensive strategies like sedation or restraint (Meindl et al., 2019; Özalp Gerçeker et al., 2020). To date, only one study has examined HMD VRET for needle fear in adults, finding that a single session of VRET reduced fear symptoms relative to a wait-list control group (Jiang et al., 2020). However, this study included only clinically diagnosed individuals, which leaves a significant gap in the literature regarding the feasibility, acceptability, and preliminary effectiveness of VRET for adults across the broader fear of needles spectrum, particularly those with subclinical symptoms.

1.8 Benefits and Challenges of Virtual Reality Exposure-Based Therapy

VRET presents several key advantages over traditional exposure-based therapy, including greater scalability, consistency across sessions, customizability of stim-

uli, declining costs, and enhanced control over the therapeutic environment (Bell et al., 2020; Bin et al., 2025). Notably, individuals are significantly less likely to refuse VRET compared to traditional in vivo exposure, suggesting greater acceptability (Garcia-Palacios et al., 2007). VRET also offers flexibility in delivery: it can be administered by a clinician in a controlled setting or self-guided at home. Like other digital health interventions, this adaptability reduces logistical barriers such as time off from work or school and the need to travel to a clinic. Increased ecological validity has also been reported with VR-delivered clinical care (Selaskowski et al., 2024).

However, VRET is not without limitations. One important limitation is VR sickness (also called cybersickness), which presents as dizziness, nausea, and other motion-sickness-related symptoms. VR sickness is primarily caused by sensory conflicts between visual and vestibular inputs (Laessoe et al., 2023; Ng et al., 2020). When an individual's visual system perceives movement within the virtual environment that is not corroborated by corresponding physical motion, discomfort can occur (Allred et al., 2025; Laessoe et al., 2023; Ng et al., 2020). Factors such as display latency, low frame rates, and the vergence-accommodation conflict, where the eyes' focus and convergence cues are mismatched, can exacerbate these symptoms (Wang et al., 2023). Accessibility remains another barrier, as widespread adoption of VR technology is still developing (Y. Yang, 2024). Moreover, there is an ongoing need to refine treatment protocols to ensure safety, usability, and clinical effectiveness across different populations.

Despite its clear advantages, VRET has not yet been fully realized as a practical alternative to traditional exposure therapy, and key questions remain about how to improve its acceptability, effectiveness, and safety. Mental health care has been identified as one of the most promising areas for applying VR technology (Li et al., 2017), but clinical adoption has been limited by a shortage of high-quality research (Selaskowski et al., 2024). Closing this gap is crucial for advancing the field and ensuring that VRET can be used widely and responsibly in real-world settings.

1.9 Aims and Objectives

The broader aim of this PhD project is to conduct early-phase evaluation of VRET as an acceptable and potentially effective intervention for two subclinical anxiety use cases: contamination-featured OCD and fear of needles. These particular use cases have received relatively limited attention in both VRET research and clinical settings, despite substantial public health consequences. Contamination-related OCD carries an estimated annual societal cost exceeding £5 billion in the UK alone (Kochar et al., 2023), while fear of needles affects between 20% and 30% of the general adult population and is associated with avoidance of vaccinations, blood draws, and routine medical care, contributing to poorer long-term health outcomes (Alsbrooks & Hoerauf, 2022; McLenon & Rogers, 2019). Despite this burden, since the commercial release of HMD VR systems only four VRET studies for OCD have been published (Cullen, Dowling, Segrave, Carter & Yücel, 2021; Fajnerová et al., 2023; Inozu et al., 2020, 2021), and only one HMD VRET study has examined fear of needles in adults (Jiang

et al., 2020). The limited clinical attention both conditions receive may itself reflect the avoidance behavior that characterizes them: individuals who avoid contaminated environments or medical settings are less likely to present to clinicians, reducing both treatment uptake and research opportunity. Moreover, they present distinct yet related anxiety profiles that may help determine whether a common treatment modality, such as VRET, can be effectively applied across symptom domains. Another objective of this project is to assess whether participants would find this form of therapy acceptable, as even the most effective interventions have limited real-world value if individuals are unwilling to engage with it.

Feasibility, as used in this thesis, is understood in line with early-phase intervention evaluation frameworks (Bowen et al., 2009). Feasibility studies are not designed to test definitive efficacy. Rather, they examine whether an intervention can be delivered as intended and whether it is acceptable to the target population, providing the evidence base needed to justify and inform the design of larger-scale trials. Relevant feasibility dimensions assessed across the case studies include: *acceptability* (whether participants found VRET an acceptable form of intervention, as measured by usability ratings and open-ended feedback), *demand* (recruitment and retention rates, indicating whether the target population is willing to engage), *implementation* (whether the protocol could be delivered as designed, including monitoring of adverse events such as VR sickness and protocol completion rates), and *limited efficacy testing* (preliminary signal of whether the intervention produces the intended anxiety response and any early symptom change). The case studies are therefore not positioned as definitive efficacy trials, but as the necessary early-phase evaluation preceding full randomized controlled trials.

This project addresses the following specific objectives:

1. To evaluate the preliminary effects of a single-session VRET intervention on anxiety and symptom severity in subclinical contamination-related OCD (Chapter 4), including whether VRET sufficiently induces anxiety to facilitate exposure, whether effects persist at one-month follow-up, and whether presence in VR is associated with outcome.
    a) Can VRET sufficiently induce anxiety to a degree that is effective for exposure therapy, both subjectively and physiologically?
    b) Is sex associated with symptom and anxiety reduction?
    c) Is physical presence in the VR environment associated with symptom and anxiety reduction?

2. To evaluate the preliminary effectiveness and acceptability of a single-session VRET intervention for subclinical fear of needles in adults (Chapter 5), including whether the intervention reduces anxiety during exposure, whether effects persist at one-month follow-up, and whether participants find it acceptable.

3. To characterize the physiological signatures of contamination OCD and fear of needles anxiety using wearable sensors and machine learning (ML),

and to assess whether physiological markers can differentiate baseline from heightened anxiety states across both conditions (Chapter 6).

4. To assess the acceptability and usability of VRET across both case studies, examining participant-reported experience and willingness to engage (Chapter 4 and Chapter 5).

This project was supported by the LISS-DTP, with industry partnership by XRHealth (previously Amelia by XRHealth, Amelia, and Psious).

XRHealth is currently the largest XR therapeutics platform globally, offering more than 140 VR environments tailored to a range of psychological conditions and already in clinical use across over 70 countries ('XRHealth', n.d.). As a partner in this project, XRHealth has committed to supplying the necessary hardware, software, technical support, and training for implementation. They have also agreed to share relevant information, such as clinician feedback from current users of specific applications, and to review proposed improvements informed by research outcomes. In addition, XRHealth has expressed interest in integrating study findings into their existing clinician training programs and supporting the dissemination of research results.

The remainder of this thesis is divided into 6 chapters, as follows:

Chapter 2 summarizes a systematic review of existing literature on the use of commercial HMD VRET for anxiety-related disorders. It highlights key research gaps including the limited attention to specific anxiety conditions (e.g., contamination OCD and fear of needles), under-researched subclinical populations, and a tendency to focus on simpler to program scenarios in VR environments. The chapter also emphasizes the importance of evaluating interventions using commercially available VR technology, as this enhances accessibility and ensures relevance by avoiding reliance on outdated or impractical hardware. The methodological quality of previous studies is assessed, and design limitations are identified to guide future research directions. This chapter is based on a paper currently under review at *Virtual Reality*, with a preprint available at PsyArXiv (Caltabiano, Akin et al., 2025).

Chapter 3 examines the descriptive overview of symptom characteristics and self-reported impact of subclinical contamination OCD and fear of needles in a UK adult sample. It addresses symptom severity and the significant impact of avoidance behaviors on daily life and help-seeking behavior. These insights inform the psychological and technological design considerations for future VRET interventions. A version of this work, focused on fear of needles, has been submitted to *Psychiatry Research Communications* and is available as a preprint on PsyArXiv (Caltabiano, Burke et al., 2025a). Findings related to contamination OCD have been added for the purposes of this thesis.

Chapter 4 focuses on a pilot study evaluating the feasibility and preliminary effects of VRET for individuals with subclinical contamination OCD. It explores the use of commercially available VR equipment in delivering exposure-based therapy and discusses how users experienced presence and plausibility in the virtual environment. The findings are examined in relation to existing literature and contribute to understanding the potential of VRET for subclinical populations with OCD symptoms. A preprint of this study has been deposited on PsyArXiv

and is currently under review at *JMIR Serious Games* (Caltabiano, Voruganti et al., 2025). Portions of this paper have been previously presented as posters at the British Association for Behavioural and Cognitive Psychotherapies (BABCP) annual conference, where our research won "Highly Commended Poster," and the LISS-DTP Winter Poster Presentation at King's College, where our research won the "People's Choice" award.

Chapter 5 reports on a study investigating the preliminary effectiveness of VRET for individuals with a subclinical fear of needles. It evaluates the use of VR to simulate needle-related scenarios and examines participant outcomes following a single-session exposure intervention. The study considers factors such as user experience, perceived presence, and plausibility of the virtual environment, with findings discussed in the context of existing literature and implications for future therapeutic applications. This study has been submitted to *Frontiers in Psychiatry* for consideration and is publicly available in preprint form via PsyArXiv (Caltabiano, Burke et al., 2025b).

Chapter 6 investigates physiological markers (i.e., heart rate, EDA, and skin temperature) as indicators of anxiety in subclinical populations with contamination OCD and fear of needles anxieties. The biological basis and relevance of these markers to anxiety are discussed, followed by a presentation of findings from a study utilizing ML techniques. This chapter emphasizes the value of objective physiological data to supplement subjective self-reports, highlighting their potential to enhance VRET for real-time feedback and adaptive therapy control, enabling safer and more tailored exposure experiences. A preprint of the study that this chapter is based on has been made available on PsyArXiv and is currently under review at *Depression and Anxiety* (Caltabiano, Shaukat-Jali & Van Zalk, 2025). In line with open science principles, all analysis and ML code is publicly available via the Open Science Framework. A portion of this paper has been presented as a poster at the LISS-DTP Summer Gathering.

Chapter 7 synthesizes the project's findings to propose future directions for VRET development. It is divided into two sections: one focused on improving exposure-based therapy protocols (e.g., session structure, safety, and efficacy) and the other on enhancing VR technology (e.g., hardware/software design). It also discusses VRET's broader implications for individual care and public health, emphasizing its potential to improve accessibility and equity in mental health services.

2 Literature Exploring Virtual Reality Exposure-Based Therapy for Anxiety-Related Disorders

ABSTRACT

Objective: The purpose of this systematic review was to comprehensively examine the empirical research on Virtual Reality Exposure-Based Therapy (VRET) for adult anxiety-related disorders using commercially available head-mounted display (HMD) systems. **Methods:** Scopus, PubMed, Ovid (Journals@Ovid, APA PsycArticles, Medline, APA PsycInfo), and Web of Science were searched in January 2024, with a supplementary search conducted in March 2025. The search was limited to publications from 2018 onward, corresponding to the commercial release of modern HMD systems. To be included, studies were required to use an experimental or quasi-experimental design, employ an HMD as the primary VR delivery device, test exposure as a stand-alone component without additive techniques such as relaxation or psychoeducation, include an exclusively adult sample, and report anxiety as an outcome measure. A total of 1097 records were identified; 30 met full eligibility criteria and were included in the final synthesis. **Results:** Of the 30 included studies, 11 examined phobias, 4 examined Obsessive-Compulsive Disorder, 13 examined public speaking or social anxiety, and 2 examined other anxiety presentations (social physique anxiety and MRI anxiety). VRET was associated with reductions in anxiety symptoms across study types, with outcomes broadly comparable to traditional exposure therapy. Of the 30 studies, 9 included any formal assessment of acceptability; among these, the majority reported that participants found VRET easy to use and acceptable as an intervention. Average methodological quality was 59.92% (SD = 8.39, range = 40.48–75.00%) on the Quality Assessment Tool for Studies with Diverse Designs (QATSDD; Sirriyeh et al., 2012), with common weaknesses including small sample sizes and absence of representative sampling. **Conclusions:** Findings suggest that VRET using modern commercially available HMDs is a promising intervention for anxiety-related disorders, with effectiveness broadly comparable to traditional exposure therapy. However, variability in study quality, small sample sizes, and inconsistent outcome measures limit the strength of conclusions and underscore the need for larger, more methodologically rigorous trials to evaluate long-term effectiveness and optimize implementation.

2.1 Introduction

Exposure therapy is a gold-standard treatment for anxiety-related disorders in which an individual who experiences a certain fear or anxiety is methodically exposed to the anxiety-provoking stimulus in a safe, controlled environment (Garner et al., 2021). This elicits anxiety to allow inhibitory learning to take place (Craske et al., 2012). Exposure therapy is conducted and has been evaluated both as a stand-alone treatment and as part of larger treatment programs, such as a course of cognitive-behavioral therapy (Garner et al., 2021). To address the rising demand for effective treatments for anxiety-related disorders, research into digital delivery methods for evidence-based interventions has been rapidly accelerating (Bucci et al., 2019). VRET, in which traditional exposure is delivered via VR, is one such digital intervention.

Advantages of VRET include its relative low cost, scalability, repeatability, and customizability (Donker et al., 2019; Gordon et al., 2020; Murray et al., 2016; Wiebe et al., 2022). A single VR application can be distributed to any number of headsets without significant increase of cost and limited maintenance expense (Wiebe et al., 2022). With VRET, environments, scenarios, and fear stimuli can be fine-tuned and personalized to an individual's specific needs. Additionally, exposure situations that would be costly or difficult to do repeatedly (e.g., flying in an airplane or receiving multiple injections), unfeasible in real-life (e.g., walking on a construction beam outside of a skyscraper for construction workers), or potentially unsafe (e.g., confronting a large aggressive dog), can become "reality" in VR. VR-based treatment has been used effectively for depression, pain management, post-traumatic stress disorder, eating disorders, dementia, attention-deficit/hyperactivity disorder, and autism spectrum disorder, among other use cases (Ioannou et al., 2020; Wiebe et al., 2022). Promising uses for VRET for anxiety-related disorders, such as specific phobias, social anxiety disorder, and OCD have also been documented (Chard et al., 2023; Ferraioli et al., 2024; Ribé-Viñes et al., 2023; Tan et al., 2024). The growing body of research in this field underscores the need for a systematic understanding of this technology's effectiveness for exposure treatment.

Delivery of VRET can be categorized into three broad methods: cave automatic virtual environment (CAVE), smartphone-based, and HMD VR. Smartphone and CAVE-based VR systems offer unique advantages and disadvantages. Smartphone-based VR utilizes low-cost headsets often made of cardboard or plastic (C. Lewis & Harris, 2022). As a result, they are highly accessible and cost-effective, making them suitable for large-scale distribution (Wiebe et al., 2022). However, their limited graphical fidelity, reduced interactivity, and lower immersion levels restrict their capacity to deliver truly immersive experiences (C. Lewis & Harris, 2022). CAVE systems provide immersive and large-scale VR environments with high-quality visuals and collaborative potential, due to the ability to view and interact with the same virtual experience as other individuals in the room, with evidence for better user experience when compared to HMDs (Tcha-Tokey et al., 2017). Nevertheless, their prohibitive cost, lack of portability, and limited individualization can be functional constraints for certain applications, such as conducting exposure-based therapy (Combe et al., 2023).

Unlike smartphone or CAVE-based systems, HMDs encompass the user's entire field of vision, integrate spatial audio, and allow for precise head-tracking, creating a fully immersive experience (C. Lewis & Harris, 2022). This level of immersion is essential for exposure therapy as it enables users to completely engage with virtual environments, enhancing psychological realism (Gromer et al., 2018; Price & Anderson, 2007). Furthermore, HMDs offer an optimal balance of affordability, portability, and customizability compared to smartphone and CAVE-based system alternatives, cementing their role as the most promising VR system for therapeutic use.

There are a number of existing systematic reviews examining the effectiveness of VR for exposure-based treatment and exploring its evolving role in anxiety-related disorders. The studies included in these reviews have demonstrated that VRET effectively reduces symptoms of anxiety and specific phobias, and noted scalability and cost-effectiveness of the VR interventions as major strengths. However, these reviews have key limitations that justify the need for an updated systematic review.

First, there has been a focus on outdated VR technology and heterogeneity in VR systems used. Many previous reviews assessed VRET using older VR technology, such as CAVE and smartphone-based VR (Oing & Prescott, 2018), which lack the immersion and interactivity of modern HMD VR (Greengard, 2019). Given rapid advancements in VR technology, conclusions drawn using older technology may not apply to today's interventions. Prior reviews also grouped studies using multiple different VR setups (i.e., CAVE, smartphone-based, and HMDs), making it difficult to compare efficacy across different modalities (Baghaei et al., 2021; Wiebe et al., 2022). It is still unclear if the choice of CAVE, smartphone, or HMD VR could affect efficacy, acceptability, or user engagement in treating anxiety-related disorders (Wiebe et al., 2022).

Comparisons with traditional in vivo exposure suggest that VRET achieves comparable reductions in fear and avoidance behaviors, though only a limited number of studies have directly tested these approaches against each other (Meyerbröker & Morina, 2021). Increased user engagement and adherence were also seen in VRET when compared to in vivo exposure (Wiebe et al., 2022). However, there is a noted lack of high-quality studies utilizing modern HMD systems, which offer the potential for greater immersion and psychological realism compared to outdated, legacy setups such as CAVE and smartphone-based VR (Oing & Prescott, 2018).

Since the advent of modern commercial HMD VR headsets, established in 2018 with the consumer launch of Oculus Go (Greengard, 2019), HMDs have displaced CAVE and smartphone-cardboard VR setups, due to progressive discontinuation by the tech industry (Combe et al., 2023; Greengard, 2019; C. Lewis & Harris, 2022). Updating the literature with a systematic review of VRET delivered through newer technology is essential, as advancements in graphics, immersion, and potential links to cybersickness may influence the effectiveness of exposure therapy.

Second, although several existing reviews have examined VR in the context of exposure or anxiety, few have systematically reviewed exposure-based interventions specifically targeting anxiety-related disorders. Some reviews have either

not systematically reviewed exposure (Baghaei et al., 2021), anxiety (Ioannou et al., 2020), or interventions per se (Meyerbröker & Morina, 2021; Wiebe et al., 2022). A systematic review of VRET is particularly crucial for anxiety-related disorders, as exposure therapy forms the cornerstone treatment for these conditions. Anxiety disorders often involve avoidance behaviors and heightened fear responses, making controlled, gradual exposure, like that provided by VRET, particularly advantageous. Furthermore, the diverse manifestations of anxiety disorders necessitate a comprehensive synthesis of evidence to identify which subtypes respond most effectively to VRET, whereas other disorders may not rely as heavily on exposure-based interventions. By isolating studies that exclusively employ exposure-based interventions without additional techniques such as relaxation or cognitive restructuring, this review aims to specifically explore whether virtual scenarios successfully trigger anxiety, a fundamental indicator that exposure has been effectively achieved.

Third, there has been limited exploration of acceptability and user experience. Previous reviews have not systematically explored acceptability and user engagement as primary objectives. Given that adherence is critical in therapeutic settings, understanding user experience is crucial.

Thus, while previous systematic reviews collectively emphasize that while VRET holds significant promise, methodological limitations in existing research, including small sample sizes, inconsistent outcome measures, lack of exploration of user experience, and a reliance on older VR systems, have hindered more definitive evidence relating to its broader applicability. These findings underscore the need for further investigation using contemporary HMD VR technology to explore preliminary effectiveness and acceptability. Following this, the current systematic review updates a previous review that included studies using earlier technology (Oing & Prescott, 2018), and also adds a focus on examining user experience and acceptability.

The current systematic review aims to address these gaps by focusing exclusively on studies using modern, commercially available HMDs, systematically reviewing VR-delivered exposure-based interventions for anxiety-related disorders, and evaluating acceptability and user experience as a primary objective. The primary goal is to assess the feasibility of this technology in treating anxiety-related disorders, while identifying gaps in the existing literature. Specifically, this review seeks to answer the following questions: 1) Is VRET with commercially available HMDs an effective and acceptable intervention for anxiety-related disorders? 2) What equipment is most commonly used? 3) What is the quality of the research being conducted? In addition, we aim to highlight existing research gaps and provide recommendations for future studies.

2.2 Methods

2.2.1 Search Strategy

The systematic review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Screening and data

charting were performed independently by two reviewers to reduce selection bias. Disagreements were resolved through discussion and consensus.

Scopus, PubMed, Web of Science, and Ovid (Journals@Ovid, APA PsycArticles, MEDLINE, and APA PsycInfo) were searched on January 16, 2024. The search strategy combined free-text and field-tagged terms (title, abstract, and keywords where available) across three concept sets: VR and HMD terms (e.g., VRET, virtual reality, head-mounted display, HMD), exposure-based intervention terms (e.g., exposure, exposure therap*, systematic desensiti*), and anxiety-related condition terms (e.g., anx*, phobi*, panic, obsessive*, compuls*), with database-specific adaptations applied. Searches were limited to English-language, peer-reviewed journal articles published from 2018 onward, corresponding to the commercial release of modern HMD systems. A sensitivity check was conducted by rerunning searches with additional synonyms, which did not change the final included set after full screening. A supplementary update search was conducted on March 15, 2025 using the same strategy. Reference lists of relevant reviews and included studies were hand-searched to identify additional eligible records.

2.2.2 Eligibility Criteria

All English-language, published, peer-reviewed studies investigating VRET for anxiety-related disorders since the commercial release of HMDs were considered. Although the broader thesis focuses on subclinical anxiety, the systematic review deliberately included studies involving clinically diagnosed populations. This decision was made for two reasons. First, the evidence base for VRET in subclinical populations is extremely limited, meaning that restricting the review to subclinical samples would have yielded too few studies to draw meaningful conclusions about the technology's effectiveness, acceptability, or protocol characteristics. Second, and more importantly, findings from clinical populations provide the closest available evidence base from which to extrapolate intervention design decisions for subclinical use, including session structure, exposure duration, outcome measurement, and acceptability. The review therefore serves as a foundation for contextualizing and interpreting the subclinical case studies reported in Chapter 4 and Chapter 5. To be included, a publication needed to (1) have an experimental or quasi-experimental design, (2) use a HMD as the primary VRET device, (3) test an exposure-based intervention without other additive techniques (e.g., breathing exercises or extensive psychoeducation), (4) have an exclusively adult sample, and (5) explore anxiety as an outcome measure. Interventions that included minor supportive elements (e.g., brief orientation or debriefing) were included, but studies that integrated substantial non-exposure-based techniques as core components were excluded.

Only publications written in English were considered for inclusion. Unpublished or non-peer-reviewed materials were not included in this review.

2.2.3 Study Selection

Following database searching and deduplication, titles and abstracts were screened for potential eligibility by both reviewers independently. Where eligibility could

not be determined from the abstract alone, a targeted review of the methods section was conducted prior to full-text retrieval. This intermediate step was adopted because records in this field frequently lacked sufficient detail in the abstract to determine whether the key eligibility criteria were met, specifically whether VR was delivered via an HMD rather than an alternative modality, and whether exposure could be evaluated as a stand-alone component rather than being embedded within a broader multi-technique intervention. Where uncertainty remained after reviewing the methods section, the full text was retrieved and assessed in its entirety. All inclusion and exclusion decisions were made independently by both reviewers, with disagreements resolved through discussion and consensus.

2.2.4 Data Collection Process and Methodological Quality Assessment

A structured data extraction method was used to develop a descriptive summary for each included study. Additionally, a methodological quality assessment was conducted independently for each study included in the final review. This assessment utilized the QATSDD, a well-established quality assessment scale designed for studies employing diverse methodologies. The QATSDD evaluates studies based on 16 criteria, with 14 items applicable to qualitative and quantitative studies and all 16 items used for mixed-methods studies. Two reviewers independently conducted the quality assessments, with any disagreements resolved through consensus. Reviewers rated each item on a scale from 0 (Not at all) to 3 (Complete), based on the information provided in the study. The final quality score was expressed as a percentage, calculated by dividing the awarded score by the maximum possible score for the given study design.

2.3 Results

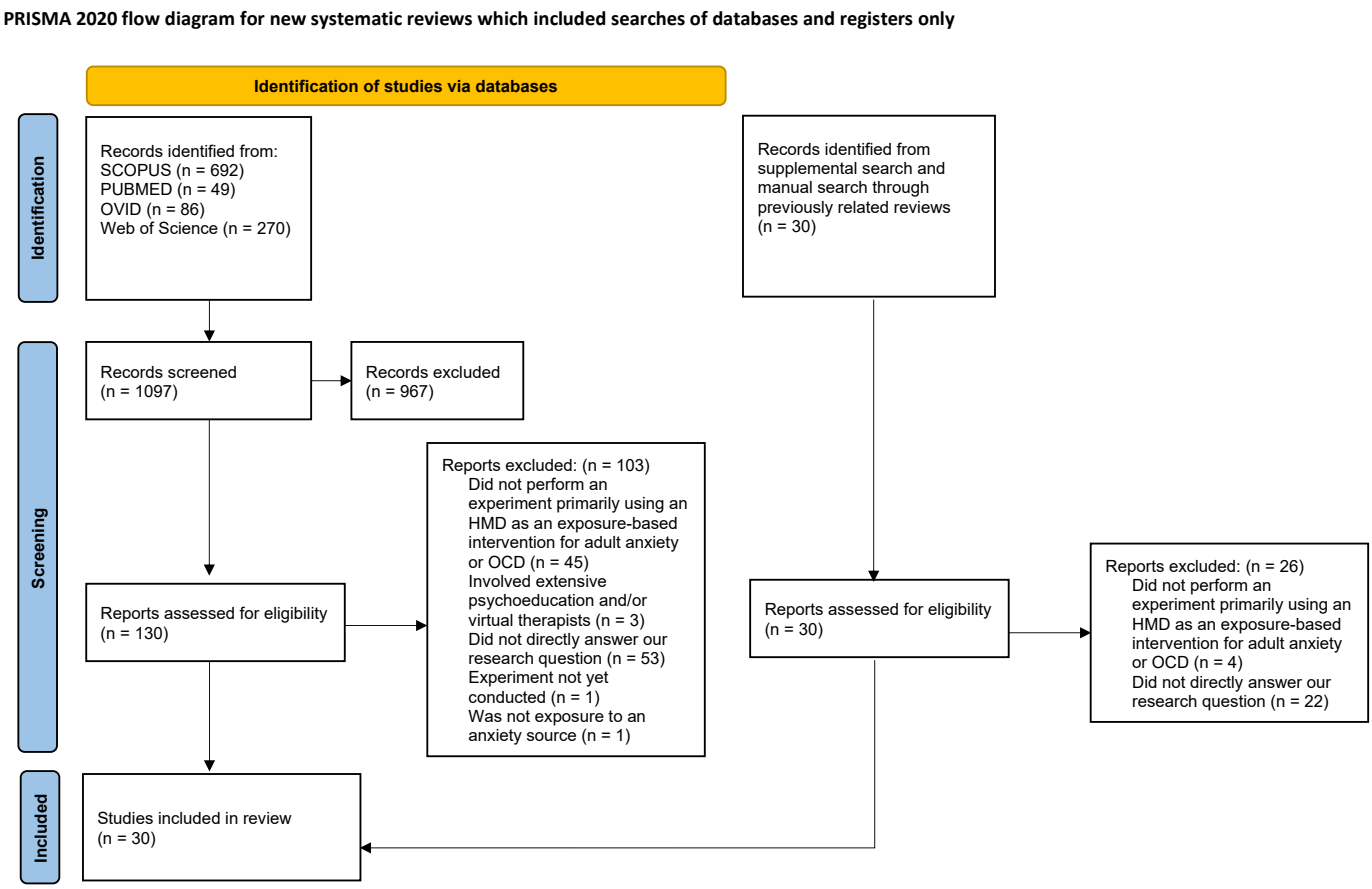
2.3.1 Study Selection

The initial search identified 1097 studies for screening. 130 studies were assessed for eligibility. A supplemental search to identify any studies published at a later date and a manual search through previously published related reviews identified a further 30 studies, of which 3 were found eligible. A final sample of 30 studies that met the inclusion criteria were included in the review. Figure 2.1 provides the PRISMA diagram demonstrating the study workflow.

Of the 30 identified studies, 11 were on various phobias (i.e., Arachnophobia, Claustrophobia, Dental phobia, Acrophobia, and Driving phobia), 4 were on OCD, 13 were on public speaking anxiety and social anxiety, and 2 were on other forms of anxiety (i.e., social physique anxiety and MRI anxiety).

A summary of the systematic review findings is displayed in Table 2.1.

Figure 2.1. PRISMA Flow Diagram



From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

For more information, visit: http://www.prisma-statement.org/

Table 2.1. Summary of Systematic Review Results

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
ARACHNOPHOBIA	Andersson et al., 2023	Participants were exposed to spiders on VR, consisting of 6 levels of increasing difficulty.	Spider fear was found to be diminished in all participants.	12 participants (9 in analysis due to attrition) with self-reported arachnophobia; ages 18 - 54 (M = 28.4); 100% female	Oculus Quest 2 cable-connected to a gaming computer	within-group paired T-tests	Spider Phobia Questionnaire, Fear Questionnaire, Behavioral Approach Test, Subjective Units of Discomfort	yes (via post-treatment qualitative phone interviews and completion rates)
ARACHNOPHOBIA	Mertens et al., 2019	Participants undertook a fear-conditioning experiment with a virtual spider as the unconditioned stimulus.	Results showed spider-fearful group had stronger differential fear conditioning.	2 groups: a spider-fearful group (n = 23, ages 18 - 26, M = 21.52, 100% female) and a non-fearful group (n = 25, ages 19 - 25, M = 21.32, 100% female)	Oculus Rift VR headset (Version CV1)	ANOVAs, t-tests, regression analyses	The Fear of Spider Questionnaire, The State-Trait Anxiety Inventory DY-2, Skin Conductance Response, Fear Potentiated Startle; *Non-Validated:* a screening questionnaire, a question for subjective fear rating assessment, a post-experimental interview	none
OCD	Cullen, Dowling, Segrave, Carter and Yücel, 2021	22 patients partook in a VRET session of a contamination environment with personalizable graded exposure tasks and a matched session of in vivo exposure.	The measures indicate virtual and in vivo exposure sessions provoke consistent anxiety profiles across the exposure hierarchy. VRET held advantage for engagement and adherence to tasks, while the therapeutic alliance was upheld.	22 participants (21 participants in analysis due to 1 excluded in data cleaning) who meet OCD diagnostic criteria according to DSM 5; ages 18 - 65, M = 32.91, 64% female	HTC Vive system with wireless adapter for the HMD and handheld wireless controllers Custom virtual environments were built in Unity software.	T-tests, ANOVAs	Yale-Brown Obsessive Compulsive Scale II, Subjective Units of Distress, State-Trait Anxiety Inventory, Session Rating Scale Version 3, Patient Adherence Scale for Exposure and Response Prevention Therapy	none
OCD	Fajnerová et al., 2023	OCD patients and a healthy control group were exposed to VRET covering four OCD dimensions. They rated their anxiety and compulsive tendencies provoked by each stimulus.	OCD group reported elevated levels of distress and compulsive behavior when confronted with VR exposure stimuli compared to the control group, but no increase in anxiety levels has been observed after the VR exposure. The subjective ratings of provoked distress and compulsive behavior are not associated with severity of OCD symptoms or perceived sense of presence. Association with cybersickness symptoms is also weak.	2 groups: OCD patients (n = 44, ages 18 - 63, Mdn = 32, 40.9% female) and healthy controls (n = 31, ages 18 - 61, Mdn = 31, 58.06% female)	HMD HTC Vive Pro with controllers	Chi-square test, Mann-Whitney U-test, correlations, Wilcoxon Matched Pairs test	Yale–Brown Obsessive Compulsive Scale, Beck Anxiety Inventory, Spielberger State-Trait Anxiety Inventory, Subjective Units of Distress scale, Subjective Units of Compulsions scale, Slater-Usoh-Steed Presence Questionnaire, Simulator Sickness Questionnaire	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
OCD	Inozu et al., 2020	Participants with high contamination fear were randomly assigned to experimental and control groups. Experimental group was exposed to 25-45 min VRET once or twice a week for 4 weeks.	Experimental group endorsed lower levels of anxiety, disgust, and urge to wash hands compared to the control group.	2 groups: experimental group (n = 9, M = 20.44, 77.8% female) and control group (n = 12, M = 21.17, 100% female)	Virtual Reality headset (Dual AMOLED 3.6" diagonal, 90 Hz, 1080 × 1200 pixels, 100° field of view)	MANOVAs, ANOVAs	PADUA Inventory Washington State University Revision Contamination Obsessions and Washing Compulsions subscale, State-Trait Anxiety Inventory, Disgust Scale-Revised, Immersive Tendencies Questionnaire, Yale-Brown Obsessive Compulsive Scale, Visual Analogue Scales	none
OCD	Inozu et al., 2021	Participants with high and low contamination fear participated in virtual scenarios with varying degrees of visual contamination and rated their level of anxiety, disgust, and urge to wash after performing the virtual tasks.	Participants with high contamination fear reported higher contamination-related ratings than those with low fear. Anxiety and disgust levels increased with increasing overall dirtiness of the virtual scenarios in both high and low contamination fear groups.	2 groups: high contamination fear defined by scoring at least 1.5 SD above the mean on the Padua Inventory Washington State University Revision Contamination Obsessions and Washing Compulsions Subscale (n = 33, ages 18 -31, M = 20.85, 87.88% female) and low contamination fear defined by scoring at least 1.5 SD below the mean (n = 33, ages 18 - 32, M = 22.33, 78.79% females)	HTC Vive HMD	MANOVAs, ANOVAs, Mauchly's test, post-hoc Bonferroni comparisons, t-tests, simple mediation analysis	Padua Inventory Washington State University Revision Contamination Obsessions and Washing Compulsions Subscale, Spielberger State-Trait Anxiety Inventory, Immersive Tendencies Questionnaire, Presence Questionnaire *Non-Validated:* self-report measures	none
PUBLIC SPEAKING ANXIETY	Denizci Nazligul et al., 2019	Novice software engineers with public speaking anxiety symptoms were randomly assigned to either VRET or CBT-based psychoeducation. VRET group received three sessions of 8-10 min VRET, where they were instructed to give speeches in three different sizes of auditoriums.	Both group conditions were found to be effective in reducing anxiety in public speaking and social situations. They were not superior to each other.	2 groups (ages 20 - 24, M = 21.36, 71.43% female): VRET group (n = 7) and CBT-based psychoeducation control (n = 7, 6 in analysis due to one drop out)	Oculus RIFT HMD	Wilcoxon signed-rank test, Mann-Whitney U-test	Liebowitz Social Anxiety Scale, Subjective Units of Distress Scale, Interaction Anxiousness Scale, Social Appearance Anxiety Scale, Brief Fear of Negative Evaluation Scale	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
PUBLIC SPEAKING ANXIETY	Takac et al., 2019	Participants with public speaking anxiety symptoms were immersed in three brief public speaking VRET scenarios. After 3 minutes of preparation, they were asked to speak for 6 minutes to virtual audience in small, medium, and large rooms.	VRET elicited significant distress in all three scenarios. Though within-scenario distress habituation was not observed, between-scenario habituation was partially supported. An increase in distress during the second scenario indicated that three consecutive speech performances were critical in achieving habituation. Brief repeated VRET scenarios using a virtual audience were effective in eliciting public speaking distress, as well as habituation.	19 non-clinical participants (ages 18 - 76, M = 35.47, 47.4% female)	Oculus Rift	ANOVAs, Bonferonni test, t-test	Social Interaction Anxiety Scale, Subjective Units of Distress Scale, Igroup Presence Questionnaire, Heart Rate	none
PUBLIC SPEAKING ANXIETY	Yadav et al., 2022	College students were asked to give 10 different oral presentations over four days (1 session on day 1, 8 sessions on days 2-3, 1 session on day 4). Days 1 and 4 involved real-life audiences while days 2-3 involved virtual audiences. Each session consisted of a 5-minute relaxation, 10-minute preparation, and a 5-minute presentation stage.	VR can alleviate public speaking anxiety, subjectively and physiologically.	55 participants from a student population with some withdrawals at various stages (ages 18 - 30, no reported mean, reported “almost equal” gender distribution)	Oculus Rift headset	linear regression, random forest regression, correlations, Fisher-Z approach, t-tests, ANOVAs, linear mixed effect model	Trait-Scale Inventory of the State Trait Anxiety, Communication Anxiety Inventory, Personal Report of Public Speaking Anxiety, Big Five Inventory, Brief Fear of Negative Evaluation survey, Reticence Willingness to Communicate score, State-Anxiety Enthusiasm, Body Sensations Questionnaire, VR Presence questionnaire, Sense questionnaire, Slater-Usoh-Steed questionnaire, *Non-Validated:* a custom-made survey of prior daily experiences, a custom-made Presentation Preparation Performance survey	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
PUBLIC SPEAKING ANXIETY	Banakou et al., 2024	Participants compared 3 conditions: single-session exposure, conventional multiple-session exposure where the same content was delivered in successive segments over 5 sessions, and a control group which interacted with a single virtual character to talk about everyday matters. One week later, participants were asked to speak on stage in front of a large VR audience.	Single-session exposure was at least as effective in reducing anxiety as multiple sessions. Both of these performed better than the control condition.	45 participants in 3 groups (age range not reported, M = 26.1, 60% female): single-session (n = 16), multiple-session (n = 14), and control (n = 15)	Oculus Rift S headset	Bayesian statistical model (equivalent to 1-way ANOVA), ANOVA, t distribution, posterior distributions	Personal Report of Confidence as a Speaker, Liebowitz Social Anxiety Scale, Implicit Association Test, State Perceived Index of Competence, State-Trait Anxiety Inventory, *Non-Validated:* a custom-made VR questionnaire	yes (open-ended questions about user experience at the end of the study's first phase and again after the second phase)
PUBLIC SPEAKING ANXIETY	Balachandran et al., 2024	Participants with high or moderately high Public Speaking Anxiety scores underwent three VR public speaking sessions over a period of three weeks.	Public speaking anxiety decreased pre to post intervention. Interview feedback was predominantly positive, suggesting that the intervention was well-received and potentially effective in addressing public speaking anxiety.	28 participants (ages 18 - 23, M = 20.06, 42.86% female): n = 17 at phase 1 and n = 11 at phase 2	Oculus Quest 2	paired t-test, content analysis	Personal Report of Public Speaking Anxiety questionnaire *Non-Validated:* interviews of VR user experience	yes (participant interviews about comfort with the technology, realism of VR scenarios, and impact of features, such as lifelike audience interactions and the integration of the slide deck presentation)
CLAUSTROPHOBIA	Francová et al., 2023	Claustrophobia patients and healthy control group were exposed to a single session VRET with 3 fear provoking scenarios: elevator, subway and underground parking lot.	VR environments have the potential to induce claustrophobic fear. The most anxiety-provoking situation was being stuck in an elevator, while subway was least provoking. Anxiety levels reported pre and post exposure did not differ significantly between the groups.	2 groups (ages 18 - 50, M = 29.9, 61% female): experimental group (n = 10) and control group (n = 8)	HTC Vive Pro HMD	Mann-Whitney U-test, Wilcoxon-signed rank test, Spearman correlation	State-Trait Anxiety Inventory, Subjective Unit of Distress Scale, Claustrophobia Questionnaire, Igroup Presence Questionnaire, Simulator Sickness Questionnaire	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
CLAUSTRO-PHOBIA	Tsai et al., 2018	Participants experienced both AR and VR enclosed elevator simulations (5 mins each, 10 min rest in between) while their heart rate variability was observed.	Both AR and VR are equally capable of triggering anxiety. AR environment produced a stronger experience for participants and caused stronger physiological reactions than the VR environment. Participants suggested that their anxiety was significantly higher in the VR environment than in the AR environment.	30 participants with no medical history of claustrophobia (ages 18 - 35, no reported mean or sex distribution)	Z800 3D Visor HMD	t-tests, ANOVAs	heart rate variability analysis, State-Trait Anxiety Inventory (modified), Technology Acceptance Model	yes (5-point survey items regarding acceptance of this technology in 4 dimensions: awareness and presence, usefulness, ease of use and playfulness)
DENTAL PHOBIA	Gujjar et al., 2019	Participants were randomly assigned to either VRET or informational pamphlet condition. VRET group received a single VRET with 5 dental scenarios while seated on a dental chair. Pamphlet group received written information about overcoming dental anxiety. Follow-up assessments were at 1 week, 3 months, and 6 months post intervention.	VRET group showed significant reduction in anxiety while pamphlet group did not. Progressing to a higher anxiety-provoking scenario resulted in higher subjective distress but lower heart rate. VRET was found to be efficacious in the treatment of dental phobia.	2 groups (age range 18 - 50 at eligibility screening at n = 84): VRET group (n = 15, M = 25.3, 53.33% female) and pamphlet group (n = 15, M = 23, 66.66% female); 2 drop outs in VRET group and 3 from pamphlet group	Oculus development kit 2 HMD with a resolution of 960 × 1080	MANOVAs, ANOVAs, t-tests, Friedman's test, Wilcoxon signed-rank test, χ^2 test	Phobia Checklist, Visual analogue scale for anxiety, Modified Dental Anxiety Scale, Dental Fear Survey, Behavioral Avoidance Test, heart rate, Verbal Rating Scale, Subjective Units of Distress Scale; *Non-Validated:* VR experience questionnaire	none
DENTAL PHOBIA	Gujjar et al., 2017	Participants were randomly assigned to either VRET or informational pamphlet condition. VRET group received a single session intervention consisting of five situational cues while seated on a dental chair. Pamphlet control group received standardized information compiled from the Academy of General Dentistry fact-sheet on dental anxiety	VRET group showed greater reduction in anxiety scores compared to control group. VRET was associated with a significant reduction in state anxiety, dental trait anxiety, and behavioral avoidance. Of the 9 treatment completers, 6 (4 from the VRET group and 2 from the control group) no longer had dental phobia at 6-month follow-up.	2 groups: VRET group (n = 5) and pamphlet group (n = 5); no reported age and sex distribution; 1 drop out from pamphlet group	Oculus development kit 2 HMD with a resolution of 960X1080 per eye	paired t-test, MANOVA, t-tests	Visual Analogue Scale-Anxiety, Modified Dental Anxiety Scale, Dental Fear Scale, Behavioral Avoidance Test, Subjective Unit of Distress Scale, Phobia Checklist, heart rate	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
DENTAL PHOBIA	Majidi and Manshaee, 2021	Participants with dentophobia were randomly assigned to either an experimental or a control group. Experimental group received eight sessions (15-min sessions per week) of VRET, which stimulated entering a dental office and undergoing dental examination. Control group did not receive any intervention.	VRET decreased dentophobia in the experimental group and this reduction was stable until the follow-up period. There was no significant difference between the two groups in dentophobia symptoms in the pre-test stage. A significant difference was observed between them in the post-test and follow-up stages.	2 groups who got a score of 25 on the Modified Dental Anxiety Scale (age range 25 - 40 at screening stage): experimental group (n = 15, M = 36.72, 46.67% female) and control group (n = 15, M = 37.24, 40% female)	HTC VIVE Pro HMD (equipped with two boxes consisting of 37 laser sensors, two displays with a resolution of 1200 x 1080 and a combined resolution of 1200 x 2160)	ANOVA, descriptive statistics, intra-subject analysis	Modified Dental Anxiety Scale, content validity index	none
DENTAL PHOBIA	Majidi and Manshaee, 2024	Participants were randomly assigned to either experimental or control group. Experimental group attended eight 15-minute sessions of VRET simulating a dental office, while the control group received no intervention.	Significant effect was found for VRET on state-trait anxiety. Post-test mean scores of state anxiety and trait anxiety decreased in the experimental group compared to the pretest scores.	2 groups (age range 25-40 at screening stage; mean age and sex distribution not reported): experimental group (n = 20) and control group (n = 20)	HTC VIVE headset (includes two boxes each containing 37 laser sensors; two panels with a resolution of 1200 x 1080, with a combined resolution of 1200 x 2160)	MANCOVAs, t-tests	State-trait anxiety inventory, content validity index	none
SOCIAL ANXIETY	Holmberg et al., 2020	Participants with social anxiety and a control group were exposed to 360-degree VR shopping center videos.	Participants with social anxiety reported higher levels of presence and significantly increased anxiety levels before, during, and after the videos, whereas controls reported no symptoms of anxiety. Socially anxious participants found the videos authentic and recommended VRET to be integrated into early stages of treatment before in vivo exposure. Anxiety responses can be triggered in patients with social anxiety using 360-degree shopping videos.	2 groups: socially anxious participants (n = 9, age range 19 - 38, M = 27.4, 11.11% female) and control group (n = 9, age range 23 - 33, M = 28.7, 11.11% female)	BOBO VR headset	nonparametric Friedman test, thematic analysis	Subjective Unit of Discomfort Scale	yes (via semi-structured interviews consisting of exploratory questions addressing the participants' anxiety ratings and their evaluation of presence, video quality, and cybersickness)

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
SOCIAL ANXIETY	Hur et al., 2021	Participants had 6 sessions of VRET, in which they introduced themselves to a virtual college student group with 3 levels of difficulty. Participants with social anxiety disorder underwent fMRI and assessments before and after treatment, while control participants underwent fMRI only once.	Social anxiety disorder group had increased neural responses during positive self-referential processing in the medial temporal and frontal cortices and increased left insular activation and decreased right middle frontal gyrus activation during negative self-referential processing, compared with control group. After VRET, participants with social anxiety disorder had reduced symptoms and exhibited greater activity in self-referential and autobiographical memory process brain regions while viewing positive words during post-intervention fMRI scans.	2 groups: socially anxious participants (n = 25, 21 completed sessions, M = 23.04, 40% female) recruited according to DSM 4 and score ≥ 82 on the Social Anxiety Disorder Scale and control group (n = 22, M = 23.95, 45.45% female). *Note: These sex distribution percentages are from Table 1 of the study's resulting paper. The validity of these numbers are uncertain due to the sex distribution, given as a ratio, is written in reverse in the text of the paper.*	VIVE (HTC Corporation) VR headset	chi-square tests, ANOVAs, Mann–Whitney U tests, MANOVAs, Wilcoxon signed-rank test, t-tests, correlations, whole-brain analysis	Social Avoidance and Distress Scale, the Korean Wechsler Adult Intelligence Test Fourth Edition (used for exclusion of participants), Social Phobia Scale (Korean version), Post-Event Rumination Scale, Personal Relevance Rating Task, fMRI data	none
SOCIAL ANXIETY	Kim et al., 2020	Socially anxious participants experienced 6 sessions of VR intervention (2 sessions in a single visit) consisting of 3 stages (introduction, core and finishing) and 3 difficulty levels (easy, medium and hard). The core stage was the exposure intervention in which participants introduce themselves to several other college students. The healthy control group had only a baseline assessment.	Compared with control group before treatment, socially anxious group showed significantly higher scores on all scales. These significant differences persisted even after treatment. In comparing VR treatment responder and nonresponder subgroups, there was no significant difference across the VR session. Findings indicated VR intervention had a significant effect on alleviation of social anxiety disorder symptoms.	2 groups: Social Anxiety Disorder participants (n = 32, ages 19 - 31 at screening stage, M = 23.12, 66% female) who met DSM 4 criteria and score ≥ 82 on a social anxiety scale and healthy control group (n = 33, age distribution not reported, M = 23.55, 49% female)	VIVE VR headset	χ^2 test, t-tests, ANOVAs	Korean Version of Beck Anxiety Inventory, Korean Version of State-Trait Anxiety Inventory, Korean Version of Social Phobia Scale, Korean Version of Social Interaction Anxiety Scale, Korean Version of Brief-Fear of Negative Evaluation Scale, Korean Version of Internalized Shame Scale, Korean Version of Post-Event Rumination Scale, Korean Version of Liebowitz Social Anxiety Scale, Korean Social Avoidance and Distress Scale *Non-Validated:* self-reported physiological scales	none

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Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
SOCIAL ANXIETY	Nason et al., 2020	Participants were randomly assigned to a 3D VR or a 2D 360° video grocery store environment, where they were asked to obtain an item and place it in their basket.	Both environments were associated with minimal adverse effects, experienced as being immersive, elicited moderate to strong anxiety responses from the participants, and were viewed as being usable modalities from an intervention perspective.	2 groups: VR group (n = 7, M = 32.00, 100% male) and 360° video group (n = 5, M = 30.00, 40% female) with a minimum Social Anxiety Disorder scale score of 4 for men and 1 for women	Oculus Rift (for both VR and 360° video)	analysis of transcripts, qualitative data analyses	Social Avoidance and Distress Scale, PTSD checklist for DSM-5, Combat Exposure Scale, Pittsburgh Sleep Quality Index, *Non-Validated:* scale for participants' reaction to VR and 360° Video, semi-structured phenomenological interview	yes (after experiencing the virtual environments, participants were interviewed about their perceptions of immersion, feasibility, and acceptability of the modality)
SOCIAL ANXIETY	Quintana et al., 2023	Participants were immersed in a control and an experimental virtual environment (4 tasks associated with social anxiety, such as starting a conversation with the clerk of a convenience store).	Experimental environment induced higher anxiety than the control environment among participants with Social Anxiety Disorder compared to healthy group. Unwanted negative side effects induced by immersions in virtual reality were higher in the Social Anxiety Disorder group. No significance was found between Canadians and Spaniards in terms of anxiety responses.	4 groups: Canadians with Social Anxiety Disorder (n = 15, M = 35.33, 53.30% female), Canadians without Social Anxiety Disorder (n = 17, M = 24.88, 76.50% female), Spaniards with Social Anxiety Disorder (n = 16, M = 23.06, 56.30% female), Spaniards without Social Anxiety Disorder (n = 21, M = 29.81, 52.40% female). Those with a Social Anxiety Disorder scale score ≥ 4 were considered clinical and those with < 2 were considered non-clinical. Age distributions not reported.	Z800 VR headset from eMagin™ and a Cube3 from InterSense™	ANOVAs, ANCOVAs, chi-square tests, uni-variate analyses of variance	Anxiety Disorders Interview Schedule for DSM-IV, Mini International Neuropsychiatric Interview Version 5.0.0, Liebowitz Social Anxiety Scale, Balanced Inventory of Desirable Responding Short Form, Immersive Tendencies Questionnaire, Simulator Sickness Questionnaire, Independent Television Commission—Sense of Presence Inventory, State–Trait Inventory for Cognitive and Somatic Anxiety, Subjective Units of Disturbance Scale for Anxiety	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
SOCIAL ANXIETY	Zainal et al., 2021	Participants were randomly assigned to either four or more sessions of VRET or waitlist. Participants were allowed to choose between the informal dinner party or the formal job interview environments for VRET. For both environments, each scene became more anxiety provoking as the VRET progressed. Questionnaires were administered at baseline, post-treatment, 3-month-follow-up, and 6-month-follow-up.	VRET resulted in greater reductions in social anxiety symptom severity, job interview fear, and trait worry, compared to waitlist. Although significant between-group differences did not emerge for change in depression, VRET led to change in depression, whereas waitlist did not. These gains were also maintained at 3 and 6 month follow-ups.	2 groups diagnosed with social anxiety disorder (age range 18 - 53, M = 23.30, 77.3% female): VRET group (n = 26) and waitlist group (n = 18)	Pico Goblin VR headset (5.5-inch diagonal screen size with 2560 × 1440-pixel resolution, 3 degrees of freedom, 92° field of view, a refresh rate of 70Hz, and 54–71 mm interpupillary distance)	multilevel modeling analyses	Mini International Neuropsychiatric Interview (based on DSM-5), Diagnostic and Statistical Manual-Fourth Edition–Text Revised-aligned Social Phobia Diagnostic Questionnaire, Social Interaction Anxiety Scale, Measure of Anxiety in Selection Interviews, Penn State Worry Questionnaire, Patient Health Questionnaire, iGroup Presence Questionnaire, Simulator Sickness Questionnaire, Subjective Units of Distress; *Non-Validated*: open ended qualitative feedback	yes (at post-treatment, open-ended feedback on acceptability with two items: Would you recommend this program to others who might have problems similar to yours? (Response format: Yes/No) Why? (Open-ended))
SOCIAL ANXIETY	Ghasempeyvandi and Torkan, 2023	Participants were randomly assigned to experimental or control group. Experimental group received 8 sessions of 30-minute and face-to-face virtual reality-based interventions. In contrast, the control group remained on the waiting list.	VRET significantly reduces symptoms of focus of attention, self-criticism, and interpretation bias in the experimental group compared to the control group.	2 groups diagnosed with Social Anxiety Disorder (age range 19 - 30, sex distribution not reported): experimental group (n = 15) and control group (n = 15)	HMD (details unspecified)	Chi-square test, MANCOVAs	Revised Interpretation Bias Inventory, Levels of Self-Criticism Scale, Social Phobia Inventory, Focus of Attention Questionnaire, *Non-Validated:* structured clinical interview	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
SOCIAL ANXIETY	Ernst et al., 2024	Participants with Social Anxiety Disorder and healthy controls were recruited for a single experimental session in which an initial neutral VR environment is first shown for 5 minutes to establish baselines and then 4 360-degree video exposure environments (sitting next to a stranger on a bench, meeting new coworkers, grocery shopping, and presenting to a crowd) were shown. Participants were then presented with the neutral environment again. Anxiety measures were taken at intervals throughout and after each exposure. A semistructured interview was conducted at the end.	During exposure, participants with Social Anxiety Disorder reported significantly higher average anxiety levels and peak anxiety levels compared to the control group during exposure. However when accounting for baseline anxiety levels, significant differences in anxiety were only found in 2 of the 4 environments.	2 groups (N = 20, age range 21 - 32, mean age not reported, 40% female): Social Anxiety Disorder group (n = 10) and healthy control group (n = 10)	HTC VIVE Pro	t-tests	Social Interaction Anxiety Scale, Subjective Units of Distress Scale, Multimodal Presence Scale, System Usability Scale, *Non-Validated:* semistructured interview on anxiety and user experience	yes (a two-part semi-structured interview on anxiety, relevance, and usability were performed before and after the session)
SOCIAL PHYSIQUE ANXIETY	Jeanningros et al., 2023	Participants experienced a virtual swimming pool environment for 10 min using a virtual reality headset, then State Social Physique Anxiety and fear of being negatively judged were measured.	State Social Physique Anxiety was found to be significantly higher in the high Social Physique Anxiety group. Fear of being judged negatively was also significantly higher in the high Social Physique Anxiety group. Unwanted negative side effects scores did not increase post-immersion in either group.	2 groups: self-identified high Social Physique Anxiety group (n = 25, age range 18 - 45, M = 40.56, 100% female) and low Social Physique Anxiety group (n = 20, age range 18 - 45, M = 26.15, 100% female)	Oculus Rift 2 headset	chi-square tests, t-tests, ANOVAs	Social Physique Anxiety Scale, Simulator Sickness Questionnaire, Weight Internalization Bias Scale, Body Appreciation Scale, Immersion Tendencies Questionnaire, Presence Questionnaire; *Non-Validated:* sociodemographic questionnaire	none

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
ACROPHOBIA	Kisker et al., 2021	Participants were randomly assigned to either height or ground condition in a virtual environment. They were instructed to walk along the construction made of virtual steel girders.	Exposed to great height, participants walked significantly slower across a virtual steel girder construction protruding from a high-rise building, compared to participants who walked the same construction on the ground level. They showed realistic psychophysiological responses. Height condition reported greater sense of presence, which indicated that emotions have an elevating effect on presence. VR evokes lifelike responses both behaviorally and physiologically.	2 groups: height condition (n = 26, 24 at analysis due to premature termination, problems with tech and procedures, M = 22.42, 65.38% female) and ground condition (n = 27, 25 at analysis, M = 21.33, 74.07% female), age ranges not reported	HTC Vive Pro HMD	Mann–Whitney-U test, hierarchical linear regression, Chi square test, t-tests	State-Trait Anxiety-Inventory (trait subscale), Acrophobia Questionnaire, Positive and Negative Affect Schedule, Igroup Presence Questionnaire, cardiovascular measurements; *Non-Validated:* questionnaire on well-being	none
ACROPHOBIA	Kodithuwakku Arachchige et al., 2023	Healthy volunteers were recruited and tested in 7 virtual environments of different heights over 3 days for about 30 minutes per day. At each environment, participants identified occupational hazards present and were asked about anxiety levels.	Participants identified the lowest number of hazards at 6-story altitude and 6-story edge, and on Day 1 compared to other environments and days. Attitude Towards Heights Questionnaire scores were lowest at ground, 2-story altitude, and 2-story edge.	28 participants (M = 20.48, 50% female), age range not reported	1st gen Oculus Go	ANOVA, simple main effects analysis	Simulator Sickness Questionnaire, Attitudes Towards Heights Questionnaire, modified State-Trait Anxiety Inventory Questionnaire, Presence Questionnaire, Physical Activity Readiness Questionnaire, heart rate	none
MRI ANXIETY	Nakarada-Kordic et al., 2020	Participants experienced a VR and non-VR mock MRI. Each session lasted 30 min, including a 20-min mock or VR scan. Ratings of anxiety and how comfortable and relaxed the participants felt were recorded at five points during and after each simulation.	No significant differences in anxiety ratings during or between the two simulations, levels of comfort between the two types of simulation, VRET realness, or how anxious, relaxed, and comfortable they felt in each environment. 65% of participants thought the mock simulation felt more real than the VRET. 86% found the VRET to be a helpful way to prepare for a real MRI exam.	20 participants (ages 19 - 52, M = 28.1, 45% female)	Vive VR headset	Friedman test, Wilcoxon signed-rank test, thematic analysis	*Non-Validated:* questionnaire modeled on previous studies covering demographic information and prior history of anxiety and claustrophobia, verbal Likert scale ranging from 1 to 5 on how anxious, relaxed and comfortable participants felt, and overall experience questionnaire	yes (Non-validated questionnaire including how the VR can help prepare for a real scan, suggestions for changes, which simulation (if any) they felt more relaxed, comfortable, and nervous. Overall experience questionnaire at study conclusion.)

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Table 2.1 – continued from previous page

Type of Anxiety	Citation	Methods	Findings	Participants	VR Equipment	Main Statistical Analysis	Measures	Measurement of Acceptability
DRIVING PHOBIA	Trappey et al., 2020	Participants with high driving fear questionnaire scores were immersed in a five-level VR environment, in which they drive for five minutes and are asked if they wish to advance to a higher level if the immersive driving environment is no longer challenging or fear inducing.	Participants' subjective distress and fear of driving were reduced significantly by the VRET.	2 groups (age range at screening stage 20 - 60, mean age not reported): treatment group (n = 30, 50% female) with high fear of driving according to the driving behavior questionnaire and control group (n = 60) with low or no fear of driving	HTC Vive Pro HMD	t-test, ANOVAs, Mann–Whitney test	Driving Behavior Survey, Driving and Riding Avoidance Scale, a pre-verified survey (self-measurement driving behavior survey adapted from previous literature)	none

2.4 Discussion

2.4.1 General Findings

Across the 30 included studies, authors frequently reported that VR-based exposure tasks elicited in-session anxiety or fear responses, indicating emotional engagement with feared stimuli. The distribution of studies indicates that phobias ($n = 11$) and public speaking or social anxiety ($n = 13$) are the most frequently investigated targets in the recent HMD-based VRET literature, accounting for 80% of included studies, whereas other anxiety-related targets, including OCD ($n = 4$) and other anxiety presentations ($n = 2$), remain underrepresented. Oculus and HTC Vive headsets were the most commonly used equipment, each used in 12 of the 30 studies, likely reflecting their commercial availability and research accessibility. In contrast, structured assessment of acceptability and user experience was reported in only 9 of 30 studies, highlighting a recurring gap in implementation-relevant outcomes. Methodological limitations were common across the evidence base, including small sample sizes (range = 10–90; $M = 36.80$, $SD = 21.06$) and variability in outcome measurement and follow-up timepoints, which constrain cross-study comparability. Although publication volume in this area has increased relative to earlier reviews (Meyerbröker & Morina, 2021; Wiebe et al., 2022), the subset of studies that evaluate contemporary HMD-delivered exposure as a stand-alone component remains relatively limited, and reporting practices are often insufficiently standardized to support strong cross-study inferences.

2.4.2 Quality Assessment

The studies had an average quality assessment score of 59.92% (SD = 8.39, range = 40.48–75.00). The scores varied across the studies, with those on phobias averaging at 58.12% (SD = 11.00, range = 40.48 - 75.00), studies on OCD averaging at 64.29% (SD = 4.35, range = 59.52 - 69.05), studies on public speaking anxiety & social anxiety averaging at 60.87% (SD = 6.66, range = 45.83 - 70.83), studies on social physique anxiety averaging at 61.90%, and an average score of 47.92% for a study on MRI anxiety. A complete table of quality assessment scores is provided in Table 2.2.

Scores varied more widely within anxiety types represented by larger numbers of studies: phobia studies showed the widest range (40.48–75.00), likely reflecting greater methodological diversity within that subfield. Across the QATSDD criteria, studies generally scored well on stating aims and objectives (criterion 2), describing data collection procedures (criterion 6), and fitting the method of analysis to the research question (criterion 12). Common weaknesses included failure to consider sample size in terms of analytical power (criterion 4), limited evidence of representative sampling (criterion 5), and absence of user involvement in design (criterion 15), with the latter likely reflecting widespread reliance on commercially developed or pre-made VR software rather than co-designed environments.

Table 2.2. Table of Quality Assessment

Criteria	Andersson et al., 2023	Mertens et al., 2023	Cullen et al., 2019	Fajnerová et al., 2021	Inozu et al., 2020	Inozu et al., 2021	Nezlişul et al., 2019	Takae et al., 2019	Yadav et al., 2020	Banakou et al., 2024	Balachandran et al., 2024	Francová et al., 2023	Tsai et al., 2018	Ghasemp eyvandi & Torkan, 2023	Ernst et al., 2024	Gujjar et al., 2019	Gujjar et al., 2017	Mejida & Mansbaee, 2021	Mejida & Mansbaee, 2023	Hur et al., 2021	Kim et al., 2020	Nason et al., 2019	Quintana et al., 2023	Zainal et al., 2021	Jeannings ros et al., 2023	Kisker et al., 2019	Kodithuwakku Arachchige et al., 2020	Nakarada-Kordic et al., 2020	Trappey et al., 2020	Holmberg et al., 2020
1	2	3	2	3	2	3	3	3	3	3	2	1	2	3	0	1	2	2	1	3	2	3	1	2	1	1	2	1		
2	3	3	3	3	2	3	3	3	3	3	3	2	3	3	2	2	2	3	2	2	3	3	2	3	3	3	3	2	1	
3	1	1	1	1	1	2	0	1	1	1	1	3	1	1	1	3	3	1	1	1	3	1	1	1	2	1	1	1	1	
4	3	3	0	1	0	0	0	0	0	1	0	0	0	2	0	2	0	2	0	1	0	3	2	0	2	1	1	0	0	
5	1	2	3	2	1	1	1	1	2	0	1	1	1	1	1	3	1	1	1	1	1	2	2	1	1	1	1	1	1	
6	3	3	3	3	3	3	3	3	3	3	2	2	2	3	3	2	3	3	3	3	3	2	3	3	2	3	3	3	2	
7	1	1	2	1	1	1	1	1	2	1	2	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	2	1	
8	2	2	2	2	2	3	1	2	1	2	2	2	1	1	2	2	1	2	2	2	3	2	2	2	1	1	1	2	1	
9	2	3	3	1	3	3	3	3	1	3	1	1	3	2	0	1	2	3	1	1	3	1	3	3	2	1	0	0	0	
10	3	2	3	3	3	2	2	3	3	2	2	3	3	3	3	3	2	2	3	3	3	2	2	2	3	3	3	3	3	2
11	3									3	3				3						3						3		3	
12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
13	2	1	2	1	1	1	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	3									2	2				3						2						0		2	
15	1	2	0	2	0	0	0	0	1	0	2	1	0	0	0	3	0	0	1	1	0	0	0	0	0	0	0	1	1	
16	3	2	2	2	2	3	3	3	3	2	3	2	0	2	3	3	2	2	2	2	3	3	2	2	3	3	2	2	2	1	2
Total (%)	75.00	73.81	69.05	66.67	59.52	61.90	61.90	61.90	64.29	62.50	70.83	52.38	40.48	59.52	62.50	66.67	45.24	64.29	59.52	59.52	50.00	68.75	57.14	66.67	61.90	54.76	52.38	47.92	54.76	45.83

1 Explicit theoretical framework
2 Statement of aims/objectives in main body of report
3 Clear description of research setting
4 Evidence of sample size considered in terms of analysis
5 Representative sample of target group of a reasonable size
6 Description of procedure for data collection
7 Rationale for choice of data collection tool(s)
8 Detailed recruitment data
9 Statistical assessment of reliability and validity of measurement tool(s) (Quantitative only)
10 Fit between stated research question and method of data collection (Quantitative only)
11 Fit between stated research question and format and content of data collection tool e.g. interview schedule (Qualitative only)
12 Fit between research question and method of analysis (Quantitative only)
13 Good justification for analytic method selected
14 Assessment of reliability of analytic process (Qualitative only)
15 Evidence of user involvement in design
16 Strengths and limitations critically discussed

2.4.3 Description of the Intervention

Among the 30 reviewed studies, significant differences existed in intervention protocol designs, with considerable variation in session numbers, durations, and methodologies. Studies commonly included between 1 and 8 sessions, with session durations ranging from 15 minutes to over an hour. A notable lack of standardization across protocols was evident (e.g., participants within the same study and across different studies experienced varying lengths of exposure sessions), complicating direct comparisons. Additionally, a number of studies failed to specify session length explicitly, as noted in the quality assessment scores for criterion 4 (Table 2.2). Outcome assessments were frequently inconsistent, typically conducted immediately post-intervention, with only a minority including longer-term follow-up assessments. Validated, disorder-specific clinical scales were commonly employed to measure symptom severity, but few studies included assessments of functional impact or general well-being. Samples often consisted of non-clinical or student populations, with limited demographic diversity reported. Study designs varied significantly, ranging from feasibility studies and single-arm case series to randomized controlled trials with active comparators.

A standardized VR protocol is illustrated in Gujjar et al.'s dental phobia study (2017), where participants were immersed in a virtual dental office and observed their avatar and a virtual dentist. Following a two-minute orientation, the dentist performed a series of procedures, including seating the participant, inspecting the mouth, administering an injection, and using a drill with and without sound. Participants sat in a real dental chair and were told to keep their mouths open to enhance immersion, though it was unclear if this was maintained throughout.

Many studies (e.g., Andersson et al., 2023; Cullen, Dowling, Segrave, Morrow et al., 2021; Inozu et al., 2021) provided clear descriptions of methodologies. However, several studies (e.g., Quintana et al., 2023; Kisker et al., 2021) failed to report key elements such as individual session length, raising questions about consistency in implementation. Other studies (e.g., Zainal et al., 2021; Inozu et al., 2020) lacked a standardized protocol, resulting in variations in participants' experiences, such as differences in the VR exposure environment, exposure duration, and the number of sessions. Quality assessment scores reflect these issues, with an average of 59.92%, indicating moderate methodological rigor.

Among the 30 reviewed studies, there was considerable variation in session numbers, durations, and intervention protocols. Some studies (e.g., Zainal et al., 2021, Majidi and Manshaee, 2021, and Gujjar et al., 2019) offered in-depth descriptions, including graphic specifications, hardware brands, and the platforms used to develop the environment, while others provided limited or no information (e.g., Ghasempeyvandi and Torkan, 2023 and Hur et al., 2021). This inconsistency reflects the broader lack of standardization in reporting practices within this research field.

12 studies (Andersson et al., 2023; Balachandran et al., 2024; Banakou et al., 2024; Denizci Nazligul et al., 2019; Gujjar et al., 2017, 2019; Jeanningros et al., 2023; Kodithuwakku Arachchige et al., 2023; Mertens et al., 2019; Nason et al., 2020; Takac et al., 2019; Yadav et al., 2022) used Oculus headsets (including Quest 2, Go, Rift, and development kit models), while 12 studies (Cullen, Dowl-

ing, Segrave, Carter & Yücel, 2021; Ernst et al., 2024; Fajnerová et al., 2023; Francová et al., 2023; Hur et al., 2021; Inozu et al., 2021; Kim et al., 2020; Kisker et al., 2021; Majidi & Manshaee, 2021, 2024; Nakarada-Kordic et al., 2020; Trappey et al., 2020) used HTC Vive headsets (including Vive Pro models). Additionally, two studies (Quintana et al., 2023; Tsai et al., 2018) employed a Z800 3D visor, one study (Inozu et al., 2020) used an unspecified dual AMOLED headset, one study (Holmberg et al., 2020) used a BOBO headset, one study (Zainal et al., 2021) used a Pico Goblin headset, and one study (Ghasempeyvandi & Torkan, 2023) did not disclose the specific headset used. The preference for Oculus and HTC Vive headsets likely reflects their commercial accessibility compared to other similar equipment. In addition, these headsets have been shown to enhance immersion and realism while offering improved graphics (Greengard, 2019), which could contribute to the effectiveness of a VRET application.

The design of the VR scenarios also played a critical role in these studies. VR intervention scenarios ranged in complexity from a sophisticated convenience store with various aisles of products and an interactive store clerk (Quintana et al., 2023), to a simple series of pre-recorded 360-degree videos in a shopping center (Holmberg et al., 2020). Increasingly intricate VR scenarios provides more lifelike simulations of reality. Interactive elements can capture subtle anxiety-related experiences that a passive environment may not, such as a socially anxious participant interacting with a store clerk while handing over their groceries. However, using pre-recorded footage to evoke responses–without requiring dynamic interaction or real-time feedback–can be a more cost- and time-effective approach for developing and deploying an intervention. 360-degree videos have also been found effective for certain anxiety-related disorders and associated symptoms (Chard et al., 2023; Stupar-Rutenfrans et al., 2017).

A recurring theme across the reviewed studies was the lack of user involvement in the development of VR environments. Most studies relied on commercially available VR scenarios (e.g., Takac et al., 2019; Yadav et al., 2019) or previously recorded 360-degree video (e.g., Nason et al., 2020; Zainal et al., 2021), which often lacked customization and context-specific tailoring. This may have limited the personalization and ecological validity of the exposure environments. Moreover, there is a lack of detailed information regarding the decision-making process and the rationale behind the design choices made during the development of the selected environments. Understanding how these environments are conceptualized and tailored is crucial, as it can provide insights into the underlying assumptions, user needs, and objectives that guided their creation. This gap in documentation makes it challenging to evaluate the suitability of the design elements and their potential impact on treatment outcomes, and highlights the need for greater transparency in the design process for future VRET studies. Greater transparency in design choices and increased user involvement in the development process could enhance the relevance, effectiveness, and ecological validity of VR exposure environments.

In addition, terminology and definitions in the field remain inconsistent, such as the varying descriptions of what qualifies as a VR experience. Some studies initially described as VR interventions had to be manually excluded upon review, as they merely presented VR content as videos on a laptop or TV screen. Other ex-

amples include the use of the terms "embodiment," "presence," and "immersion," which carry distinct meanings across psychology, engineering, and everyday language. In addition, the precise definition of VR sickness, methods to measure it, as well as whether participants can experience its symptoms without reporting full VR sickness, varies across studies (e.g., Gujjar et al., 2017 compared to Nason et al., 2020). Some studies used inconsistent terminology to describe VR elements and exposure tasks, potentially contributing to variability in reported outcomes (e.g., the use of "presence" in Zainal et al., 2021 compared to its use in Quintana et al., 2023). These inconsistencies make study screening more challenging, complicate the interpretation of findings, and hinder cross-study comparisons.

2.4.4 Effectiveness Outcomes

Across the 30 included studies, the majority reported reductions in anxiety-related symptoms from pre- to post-intervention, with most authors interpreting findings as consistent with a therapeutic effect of VRET. However, given the substantial heterogeneity in study designs, outcome measures, comparator conditions, and follow-up timepoints, a quantitative synthesis was not conducted, and findings are summarized descriptively. Where reported, standardized effect sizes (Cohen's d, Hedges's g, and Pearson's r) were generally large, consistent with meta-analytic estimates from prior reviews of VRET for anxiety-related disorders (Carl et al., 2019; Powers & Emmelkamp, 2008). However, effect size reporting was inconsistent across studies, and several did not report effect sizes at all. Studies with active comparators, such as in vivo exposure (Cullen, Dowling, Segrave, Carter & Yücel, 2021) or psychoeducation (Denizci Nazligul et al., 2019), generally found VRET to be broadly comparable to these conditions rather than superior. The majority of outcome assessments were conducted immediately post-intervention; only a minority of studies included longer-term follow-up, limiting conclusions about the durability of effects. Comparator conditions varied substantially across studies, ranging from waitlist controls and psychoeducation to active in vivo exposure, and several studies used single-arm designs with no comparator condition, further constraining cross-study comparison.

2.4.5 User Acceptability Considerations

Although VRET remains in its early stages of clinical research, research has primarily focused on evaluating its efficacy. Few have systematically examined feasibility, such as the practicality of delivery, adherence, or recruitment processes, and even fewer have reported structured assessments of user acceptability. This pattern differs from standard intervention development models, such as those outlined by the United Kingdom Medical Research Council and the National Institute for Health and Care Research, which emphasize feasibility and acceptability testing in the early phases of intervention development (Skivington et al., 2021). One possible explanation is the influence of commercially developed VR platforms, where user testing may take place in-house and remain unpublished in academic outlets. As a result, formal reporting on these aspects may lag behind technological innovation and implementation.

While further studies are needed to probe the effectiveness of VRET as an intervention, understanding its acceptability is equally critical yet remains underexplored. Even the most effective intervention will struggle to gain adoption if it is not acceptable to users. In addition, the lack of standardized measures of acceptability and user experience remains a significant limitation of the research to date. Establishing standardized metrics in this area would enable future studies to more effectively assess and enhance this crucial aspect of VRET interventions.

Only nine studies (Andersson et al., 2023; Balachandran et al., 2024; Banakou et al., 2024; Ernst et al., 2024; Holmberg et al., 2020; Nakarada-Kordic et al., 2020; Nason et al., 2020; Tsai et al., 2018; Zainal et al., 2021) included any assessment of acceptability. One study on arachnophobia (Andersson et al., 2023) assessed acceptability through phone interviews, while another study on claustrophobia (Tsai et al., 2018) used a questionnaire evaluating user experience and acceptance based on awareness and presence, usefulness, usability, and playfulness. No studies on OCD included acceptability measures, whereas six studies on public speaking and social anxiety (Balachandran et al., 2024; Banakou et al., 2024; Ernst et al., 2024; Holmberg et al., 2020; Nason et al., 2020; Zainal et al., 2021) assessed it through interviews and open-ended feedback. The study on social physique anxiety (Jeanningros et al., 2023) did not measure acceptability, while the study on MRI anxiety (Nakarada-Kordic et al., 2020) used questionnaires with non-validated questions to gauge overall experience and gather feedback for improving the VR application. Across the nine studies that formally assessed acceptability, participants consistently rated VRET positively in terms of ease of use, engagement, and treatment acceptability. Key factors influencing acceptability included ease of use, perceived realism, and reduced barriers compared to traditional in vivo therapy.

VR sickness (i.e., cybersickness) and discomfort are crucial factors in determining user acceptability. Among the five studies that assessed VR sickness (Fajnerová et al., 2023; Francová et al., 2023; Jeanningros et al., 2023; Kodithuwakku Arachchige et al., 2023; Quintana et al., 2023), it was identified as a potential barrier for some participants, particularly when using older or less advanced VR systems with lower-quality graphics. These findings highlight the significance of hardware advancements in enhancing user experience and minimizing discomfort. As VR technology continues to evolve, addressing these concerns will be essential for broader adoption and improved treatment outcomes. By understanding and mitigating VR sickness, developers and clinicians can ensure that VR applications—especially in therapeutic contexts—are effective, comfortable, and accessible to a wider range of users

2.4.6 Limitations

This systematic review is not without its limitations. Inter-rater agreement between the two screeners was not formally quantified using Cohen's kappa at either the abstract or full-text screening phases, which is a limitation of the reporting of this review. Additionally, while initial consultation with a librarian was undertaken during search strategy development, the strategy was not formally developed with dedicated librarian support and database-specific MeSH

terms were not systematically applied, which may have affected search comprehensiveness. As VRET is still an emerging approach for treating anxiety-related disorders, its related terminology remains unstandardized. To identify studies using pure VRET exposure, we aimed to use inclusive search terms; however, some eligible studies may have been inadvertently overlooked. Additionally, the lack of standardized reporting on VR equipment may have introduced errors, as we were unable to include studies that did not explicitly specify the use of an HMD as their primary VR device. These limitations might have affected the accuracy of the presented findings.

2.4.7 Strengths

Though these limitations warrant consideration, this review also has several strengths. First, we have concentrated on studies conducted since the introduction of commercially available HMDs to ensure an accurate reflection of the most widely accessible and commonly used VR technology. Second, we have provided a comprehensive view of VRET's application across anxiety-related disorders as a whole, striking a balance between specificity and breadth. This approach enables meaningful comparisons and highlights VRET's versatility by focusing on disorders that share common underlying characteristics (i.e., avoidance behaviors and heightened threat sensitivity), which are theoretically responsive to exposure-based interventions. This selection strategy also facilitates the interpretation of therapeutic mechanisms, as observable increases in anxiety during VRET sessions provide evidence that effective exposure was achieved.

2.4.8 Recommendations for Future Research

This systematic review highlights that VRET using modern equipment effectively elicits anxiety and shows promise as an intervention for specific phobias, OCD, public speaking and social anxiety, social physique anxiety, and MRI anxiety. However, other use cases, such as agoraphobia and needle phobia, are likely well-suited for VRET interventions yet remain underexplored. Use cases examined in this review, such as VRET for OCD, should be replicated and further explored using more rigorous methodologies and larger, more representative sample sizes. Additionally, future research should assess the long-term efficacy and sustainability of VRET across various anxiety-related disorders, determining whether treatment effects persist over time. Investigating best practices for protocol standardization, including optimal session length, frequency, and customization, will be essential to maximizing treatment effectiveness. Moreover, studies should explore factors influencing user engagement, acceptability, and adherence to ensure VRET is both effective and widely accessible for clinical implementation.

Furthermore, research in this field must work toward standardizing both the vocabulary surrounding VRET and the methods used to assess acceptability. The lack of consistency in terminology—such as how "immersion," "presence," and "embodiment" are defined—complicates cross-study comparisons and limits the ability to build upon previous findings. Similarly, standardized acceptability measures are essential to ensure that future studies can reliably assess user exper-

ience, engagement, and adherence to VRET interventions. Developing validated tools for measuring acceptability will not only facilitate more robust comparisons across studies but also help identify key factors that influence user adoption and long-term implementation in clinical settings. Establishing standardized metrics will thus be critical in advancing VRET as a viable and widely accepted intervention for anxiety-related disorders.

2.4.9 Clinical Implications

Findings from this systematic review suggest that VRET using modern equipment is a promising alternative or complement to traditional in vivo exposure therapy for phobias, OCD, public speaking and social anxiety, and other anxiety-related disorders. Its ability to provide customizable, repeatable, scalable exposures in a cost-effective way offers benefits over traditional exposure. As VRET technology becomes more affordable and widely accessible, its potential for implementation across various settings expands significantly. It could be integrated into traditional clinical environments, used as an interim intervention for patients on waitlists, or even deployed in home-based treatment programs under professional guidance. This increased accessibility has the potential to bridge critical gaps in mental health care, particularly for individuals with anxiety-related disorders who may face barriers to traditional therapy, such as geographic limitations, financial constraints, or stigma associated with seeking in-person treatment. By offering a scalable and flexible solution, VRET could enhance early intervention efforts, provide continuous support between therapy sessions, and ultimately improve treatment outcomes for a broader population.

Conclusions

This systematic review highlights the potential of VRET using modern HMDs as an effective intervention for anxiety-related disorders. Comparable to traditional in vivo exposure, VRET offers enhanced accessibility and scalability, and it allows for tailored virtual scenarios that can be adjusted in real time to match individual fear hierarchies or accommodate otherwise impractical or unsafe exposures. Despite promising results, limitations such as small sample sizes, methodological inconsistencies, and lack of focus on user experience suggest the need for further research. Future studies should focus on standardizing protocols, assessing long-term outcomes, and exploring technological advancements to enhance therapeutic effectiveness. VRET represents a significant innovation in exposure-based interventions, but ongoing research is needed to establish its broader clinical applicability. The findings of this review directly inform the two case studies reported in this thesis. The review confirmed that OCD and fear of needles are substantially underrepresented in the VRET literature relative to conditions such as acrophobia and social anxiety, providing a clear justification for their selection as case study targets. The review also established that single-session protocols are represented in the existing literature and that large effect sizes have been reported even with brief interventions, supporting the single-session design adopted in both case studies. Furthermore, the review identified acceptability and user

experience as systematically underreported outcomes, directly motivating their inclusion as primary outcomes alongside preliminary effectiveness in Chapter 4 and Chapter 5.

3 Features and Characterization of Subclinical OCD and Fear of Needles Symptomatology

ABSTRACT

Background and objectives: Despite their public health significance, subclinical fear of needles and contamination anxiety are understudied. This study aimed to provide a descriptive overview of symptom severity and life interference associated with fear of needles and contamination anxiety in a UK adult sample, and to examine associations of age and sex with these outcomes. **Methods and design:** UK-based adults ages 18–80 ($N = 396$) completed an online survey assessing general demographics (age, sex, lifetime psychiatric diagnoses) and fear of needles and contamination OCD symptom severity and life interference. **Results:** Over half of participants (51.01%) endorsed sometimes to always exhibiting avoidance behavior due to contamination fears without an OCD diagnosis, and 77.02% endorsed at least some life interference from fear of needles without formal diagnosis or treatment. Younger age was associated with greater severity of fear of needles. Sex was not significantly associated with either symptomatology. **Conclusions:** Subclinical fear of contamination and needles with associated life interference is prevalent across a broad adult age range in the UK general population. These findings underscore the public health relevance of subclinical presentations and highlight the need for accessible interventions targeting these populations, including digital approaches such as VRET, to reduce avoidance of essential healthcare and improve quality of life.

3.1 Introduction

Anxiety-related conditions represent a growing public health concern. Recent data indicate that over 4% of the global population is impacted by at least one anxiety disorder, and the number of cases has increased by more than 55% from 1990 to 2019 (Javaid et al., 2023). Despite this sharp rise, subclinical manifestations of anxiety-related disorders, such as OCD and specific phobias, in particular fear of needles, remain underexplored.

Although OCD has been classified separately from anxiety disorders in the DSM-5 in view of its clinical distinctiveness, the overlap between OCD and anxiety disorders is well-established (Fontenelle & Hasler, 2008; Sharma et al., 2021). Fear of needles, also called *needle phobia* or *trypanophobia* (here referred to as fear of needles), and contamination-related OCD, one of the more prevalent and potentially treatment-resistant subtypes of OCD (Franklin & Foa, 2011; Mathes et al., 2019), are linked in their extensive public health implications. For example, receiving adequate medical care, including vaccinations and blood draws, and the ability to visit potentially contaminated environments, such as visibly unclean public bathrooms, are important for maintaining health and quality of life.

Symptoms of phobia and OCD-related disorders exist on a spectrum (Vigne et al., 2019). Hence, a greater understanding of these symptoms and their characteristics, even at levels below standard clinical threshold, is warranted.

Subclinical individuals do not meet diagnostic criteria as they fall below the clinical threshold. These individuals with symptoms below diagnostic thresholds and undiagnosed individuals, who have not sought or had the opportunity to be diagnosed, are often excluded from receiving formal treatment. Additionally, as with fear of needles, certain symptomatologies are not commonly diagnosed, potentially due to avoidance behavior, which can prevent an individual from disclosing fear to clinicians or seeking treatment (Castagna et al., 2018).

Although there is growing research on subclinical anxiety symptoms, particularly in relation to risk factors and longitudinal outcomes, there remains limited investigation into targeted interventions for this group. This is particularly true for studies exploring digital therapies such as VRET, despite evidence that subclinical symptoms are associated with significant comorbidity and often precede clinical diagnoses (Ströhle et al., 2018). For example, subclinical Generalized Anxiety Disorder increases the risk of developing and exacerbating comorbid psychiatric and somatic conditions, which in turn escalate economic burden (Haller et al., 2014).

Fear of needles and contamination prevent individuals from engaging in necessary activities, lowering their overall quality of life and resulting in public health implications. Given this, more focus should be given to understanding the degree to which these fears interfere with daily experiences through avoidance of critical activities or significant distress while completing these activities. With better understanding of these populations, we may be better able to identify who can benefit from treatment.

Assessing avoidance or life interference rather than symptom severity addresses the challenge of determining the relative clinical severity of different symptoms. For the purposes of fear of needles, it is easy to avoid experiences with needles,

as they fall outside the sphere of typical daily life. Thus, how much the fear interferes with one's life is a better indicator of subclinical symptomatology. For contamination fears, experiencing visibly contaminated environments, such as dirty public toilets, are more a part of day-to-day experience. Therefore, avoidance is a more meaningful threshold.

3.1.1 Aims and Objectives

The aim of this study is to provide an initial descriptive mapping of OCD and fear of needles symptoms, alongside their associated life interference in a sample of UK adults. Rather than estimating population prevalence, which would require a fully probability-based representative sample, this study is designed to characterize patterns of symptom occurrence, severity, and life interference within a broad community sample. This distinction informed several design decisions: participants were recruited via Prolific, a platform that provides access to a large and diverse pool of UK adults and has demonstrated superior data quality compared to other online recruitment platforms (Douglas et al., 2023), and an a priori sample size calculation was conducted to ensure sufficient power for the descriptive and associative analyses planned, rather than to achieve a specific margin of error for a population prevalence estimate. The goal is therefore to establish an initial descriptive picture of these symptom profiles and their functional impact across a range of severity levels, rather than to quantify the proportion of the UK population meeting a clinical threshold. We examine the association of sex and age with symptom severity and avoidance/life interference. We also explore individual symptoms (e.g., visiting a hospital, giving blood, and watching surgery on television) that correlate with avoidance behavior/life interference for both fear of contamination and fear of needles.

3.2 Methods

3.2.1 Participants

Participants were recruited via Prolific, an online research platform that provides access to a large pool of pre-screened adults who have opted in to participate in academic research. Prolific allows researchers to specify inclusion criteria, and in this case recruitment was restricted to English-speaking, UK-based adults aged 18 and over. Eligible participants were redirected from Prolific to an online Qualtrics survey to complete the study measures. Prolific uses a non-probability convenience sampling approach; the platform does not guarantee a fully representative sample of the UK population, but has been shown to produce higher data quality and more attentive responding compared to other crowdsourcing platforms such as Amazon Mechanical Turk (Douglas et al., 2023). An a priori sample size calculation with 95% confidence and a $\pm 5\%$ margin of error resulted in a required sample size of 385 participants. The demographic characteristics of the final sample are reported in the Results section.

Ethical approval was given by the Imperial College Research Governance and Integrity Team (Reference number: 6886495) prior to start of study.

3.2.2 Measures

Demographics. Participants self-reported age, sex, and if gender identity was the same as sex registered at birth.
Psychiatric diagnosis. Participants self-reported lifetime psychiatric diagnoses.
Fear of needles history. Participants self-reported history of fainting from the sight of blood and formal diagnosis and/or treatment for fear of needles.
Fear of needles symptoms & interference. To assess fear of needle symptom severity and life interference, we used the blood-injection-injury subscale of the Specific Phobia Questionnaire (SPQ) for interference ($\alpha = 0.94$) and extent of fear ($\alpha = 0.92$), and the injections and blood subscale ($\alpha = 0.88$) of the Medical Fears Survey (MFS) (Olatunji et al., 2012; Ovanessian et al., 2019). Participants were also asked if they have a condition requiring frequent injections or blood draws and/or have family member(s) with a fear of needles (Alsbrooks & Hoerauf, 2022; Milovanović et al., 2017).
OCD. Participants self-reported contamination-featured OCD symptoms using the Washing subscale ($\alpha = 0.82$) of the Obsessive Compulsive Inventory-Revised (OCI-R; Foa et al., 2002). In addition, one question (i.e., "How often do you find yourself *avoiding* public toilets for fear or worry that they might be too dirty?") was developed to assess self-perception of avoidance. Responses were on a 5-point Likert scale (Table 3.2).

3.2.3 Data Analysis

Statistical analyses were performed with R 4.4.0. T-tests and linear regressions were conducted to investigate the association of sex and age with severity and life interference of fear of needles. A square-root transformation was applied to symptom severity (OCI-R contamination, SPQ, and MFS) and life interference variables (SPQ) to reduce skewness and kurtosis prior to analyses. This transformation was chosen over other methods to preserve zero values, reduce variance in larger values, and retain the data's original structure, while maintaining simple interpretation (Tabachnick et al., 2019). Correlations between individual symptoms and interference were also examined and adjusted using the False Discovery Rate method to account for multiple comparisons. Missing data was addressed using Random Forest (MissForest R package), which has outperformed leading imputation techniques (Stekhoven & Bühlmann, 2012). Post imputation values were rounded to the nearest whole number to maintain consistency with original questionnaire response format. Statistical significance was defined at $p < .05$.

3.3 Results

A total of 504 participants provided consent and completed the online survey. Of these, 108 did not correctly answer attention-check questions, leaving 396 participants in the final sample. The sample was 64.90% female. 98.74% reported their gender matching sex at birth.

Participants were aged 18-80 ($M = 40.03$, $Mdn = 37$, $SD = 12.97$). 8.33% ($n = 33$) reported a history of fainting from the sight of blood, but only 0.25%

($n = 1$) reported a formal diagnosis and/or treatment of fear of needles. 4.29% ($n = 17$) reported a diagnosis of OCD. 10.61% ($n = 42$) stated having a condition requiring frequent injections or blood draws. 22.47% ($n = 89$) reported having family member(s) with a fear of needles. 33.33% ($n = 132$) screened positive for fear of needles according to the SPQ.

Table 3.1 displays occurrence of symptom severity and interference, as well as t-tests comparing males and females, with no sex differences regarding the severity of contamination fears, avoidance due to contamination fears, severity of fear of needles, or interference due to fear of needles.

Table 3.1. Occurrence of Severity and Avoidance/Interference of Fear of Contamination and Needles by Sex

	Full Sample $N = 396$	**Female** $n = 257$	**Male** $n = 138$	
	Mdn (SD)	Mdn (SD)	Mdn (SD)	t-value (df)
Contamination Fears Severity (OCI-R)	1.00 (2.54)	1.00 (2.41)	1.00 (2.79)	-0.68 (263.09)
Contamination Fears Avoidance[a]	2.63 (1.12)	2.69 (1.12)	2.51 (1.12)	1.47 (279.92)
Fear of Needles (MFS)	2.00 (2.73)	2.00 (2.92)	2.00 (2.30)	1.46 (298.58)
Fear of Needles Interference (SPQ)	4.00 (9.62)	4.00 (9.77)	5.00 (9.39)	-1.23 (292.82)
Fear of Needles Severity (SPQ)	14.00 (11.33)	14.00 (11.83)	13.00 (10.30)	1.52 (292.99)

Note. All non-normally distributed variables underwent square root transformation prior to t-tests. One participant did not identify as male or female. No p-value was significant.

In examining the effect of age on contamination fear, the linear regression model was statistically significant ($F(1, 394) = 17.28$, $p < 0.001$). Older ages were associated with a decrease in the square root of contamination score ($B = -0.02$, $SE = 0.00$). For using age to predict contamination fear avoidance, the linear regression model was not statistically significant ($F(1, 394) = 1.92$, $p = 0.167$).

Older age was associated with a lower square root of the severity of fear of needles as measured by the SPQ ($B = -0.01$, $SE = 0.01$, $p = 0.015$) as well as with the MFS ($B = -0.02$, $SE = 0.00$, $p < 0.001$). The linear regression model predicting the effect of age on extent interference on daily life was not statistically significant ($F(1, 394) = 1.71$, $p = 0.192$).

Table 3.2 examines the frequencies of item endorsement relating to avoidance/life interference.

Table 3.2. Frequencies of Item Endorsement Relating to Avoidance/Interference

	0 no interference $n(\%)$	1 $n(\%)$	2 $n(\%)$	3 $n(\%)$	4 extreme interference $n(\%)$
Contamination Fears Avoidance	73 (18.43)	109 (27.53)	126 (31.82)	67 (16.92)	21 (5.30)
Fear of Needles Interference (SPQ)					
Watching someone else get an injection	336 (84.85)	33 (8.33)	19 (4.80)	6 (1.52)	2 (0.51)
Getting minor surgery	202 (51.01)	91 (22.98)	62 (15.66)	31 (7.83)	10 (2.53)
Watching someone else getting stitches	324 (82.03)	34 (8.61)	27 (8.84)	7 (1.77)	3 (0.76)
Visiting a hospital	245 (61.87)	78 (19.70)	44 (11.11)	24 (6.06)	5 (1.26)
Giving blood	268 (67.68)	71 (17.93)	30 (7.58)	16 (4.04)	11 (2.78)
Having your blood pressure taken	316 (79.80)	46 (11.62)	25 (6.31)	8 (2.02)	1 (0.25)
Visiting the dentist	197 (49.87)	83 (21.01)	65 (16.46)	33 (8.35)	17 (4.30)
Watching someone else give blood	324 (81.82)	44 (11.11)	19 (4.80)	4 (1.01)	5 (1.26)
Watching surgery on television	310 (78.48)	50 (12.66)	19 (4.81)	11 (2.78)	5 (1.27)
Attending to someone else's cut	270 (68.70)	68 (17.30)	37 (9.41)	14 (3.56)	4 (1.02)
Attending to your own cut	274 (69.19)	77 (19.44)	25 (6.31)	18 (4.55)	2 (0.51)
Receiving an injection	254 (64.47)	89 (22.59)	22 (5.58)	21 (5.33)	8 (2.03)
Developing an illness	169 (42.89)	79 (20.05)	76 (19.29)	48 (12.18)	22 (5.58)
Blood tests	247 (62.69)	83 (21.07)	33 (8.38)	21 (5.33)	10 (2.54)

Note. Contamination Fears Avoidance was measured on a Likert scale of: 1 (Never), 2 (Rarely), 3 (Sometimes), 4 (Often), 5 (Always); the scale points were standardized for ease of presentation. This table represents data pre-imputation.

Each individual SPQ interference item was significantly correlated with the total SPQ interference score after False Discovery Rate correction ($r_s = .52 - .78$, all $p < .001$), confirming the internal coherence of the scale. The total OCI-R contamination score was also significantly correlated with the contamination avoidance item ($r_s = .40$, $p < .001$), indicating that greater contamination symptom severity was associated with greater self-reported avoidance of public toilets.

To examine the characteristics of individuals with subclinical fear of contamination and those who meet clinical threshold but remain undiagnosed, we identified individuals who endorsed a 3 (Sometimes), 4 (Often), or 5 (Always), but did not report an OCD diagnosis ($n = 202$, 64.85% female, age $= 20 - 79$, $Mdn = 37$, $SD = 13.14$), composing 51.01% of the full sample. These individuals had a median endorsement of a 3 (Sometimes) for how often they avoided dirty public

toilets (Contamination Fears Avoidance; $SD = 0.66$) and a median contamination fears severity (Contamination OCI-R) of 2 ($SD = 2.79$, range $= 0 - 12$).

Results for individuals who reported life interference due to fear of needles without a formal diagnosis and/or treatment ($n = 305$, 77.02% of overall sample) are shown in Table 3.3. These were majority female (63.28%) and ages $18 - 80$ ($M = 39.89$, $Mdn = 37$, $SD = 12.98$). 9.18% reported having fainted from the sight of blood, 10.82% reported having a condition requiring frequent injections or blood draws, and 24.59% had family members with a fear of needles.

Table 3.3. Individual Characteristics of Symptomatic Individuals Reporting Life Interference for Fear of Needles

	M	Mdn	SD	range
Symptom Severity (MFS)	3.04	3	2.81	0 - 12
Life Interference (SPQ)	10.20	7	9.69	1 - 46
Symptom Severity (SPQ)	18.24	16	11.28	0 - 54

3.4 Discussion

Understanding how fears of contamination and needles disrupt daily life and medical care in the general population is essential to guide both individual treatment and broader public health efforts. These fears can be significantly disruptive in daily life and in medical contexts, even when they do not meet formal diagnostic thresholds, such as during vaccinations or blood draws. Our findings indicate a high prevalence of both fear of contamination and fear of needles across a broad adult age range, underscoring the importance of early identification and intervention.

The occurrence of fear of needles in the current study (33.33%) is higher compared to prior work (26.2%; Freeman et al., 2021), which could be due to differences in sampling, recruitment methods, and impact of experiences with needles during the COVID-19 pandemic. The 40.08% prevalence of contamination-related anxiety in our sample is lower than COVID-era reports of new OCD symptoms (60.3%) and washing compulsions (53.8%; Abba-Aji et al., 2020). However, it exceeds pre-COVID prevalence estimates (28.2%; Ruscio et al., 2010), suggesting some pandemic-related elevation may persist. To our knowledge, there have not been comparable post-COVID estimates.

Notably, we found no significant sex differences in the severity or interference associated with either fear of contamination or fear of needles. This is in line with some prior literature (e.g., Milovanović et al., 2017), but contrasts with other previous research that has reported sex-based differences, often with higher fear in females (Olatunji, Arrindell & Lohr, 2005; Olatunji, Sawchuk et al., 2005). The absence of such sex differences in our sample suggests that these fears may not be inherently sex-specific, though further investigation is warranted.

With respect to age, our findings suggest that older participants reported less fear of both needles and contamination, aligning with prior studies (e.g., 24% of adults and 63% of children reporting needle fear; Taddio et al., 2012; lower

contamination obsessions and washing compulsions in older adults compared to younger adults; Williams et al., 2017). However, as age explained only a modest portion of the variance, other contributing factors (e.g., frequency of exposure to medical procedures or differences in health anxiety) likely play a role. For contamination fears, reduced severity with age may reflect habituation, shifts in responsibility, or differing life contexts, though longitudinal studies are needed to clarify these patterns.

Our exploratory findings highlight the need to identify individuals with fear of needles and fear of contamination for early intervention. Notably, 26.01% of participants reported a family member with needle fear, in line with prior findings (33.2%; Milovanović et al., 2017). This highlights a potential intergenerational component, suggesting family-centered interventions may be useful.

Despite the high prevalence of symptoms, only a small portion of participants had received a diagnosis or treatment (4.29% for contamination anxiety; 0.25% for needle fear). Therefore, interventions should be focused toward the general population. Public health efforts could take the form of online interventions designed to be accessed at home (e.g., using Virtual Reality Exposure Therapy), which would enable those with life-interfering symptoms to benefit from management strategies before their symptoms escalate to become a greater burden on the healthcare system. Future research should explore age-tailored interventions to improve effectiveness and increase uptake of essential healthcare like vaccinations and blood donation.

There are several limitations to the study that necessitate a cautious interpretation of the findings. First, while the sample was predominantly female (64.90%), sex was not significantly associated with fear of contamination and needles symptom severity or life interference. Nevertheless, lack of other demographic data and potential confounding variables (e.g., ethnicity, socioeconomic status, comorbid physical or mental health conditions, vaccine hesitancy, history of medical trauma, and general anxiety sensitivity) limits our ability to assess broader generalizability. Second, the cross-sectional design precludes inferences about causal relationships or the persistence of symptoms over time, and the self-selected nature of the online sample may introduce professional respondent bias.

Despite these limitations, our study provides unique insights into fear of contamination and needles by highlighting their pervasiveness in the general UK population. Even though we relied on an online sample, Prolific participants are more likely to provide meaningful responses, take their time, be attentive, and follow instructions compared to participants on other platforms (e.g., Amazon Mechanical Turk, Clickworker, Appen; Douglas et al., 2023). Our findings thus offer a first descriptive snapshot of fear of contamination and needles in a UK adult sample and underscore the importance of future work using longitudinal and demographically representative designs.

4 Case Study I: Virtual Reality Exposure Therapy for Obsessive-Compulsive Disorder Symptoms

ABSTRACT

Background: Exposure-based therapy is the gold-standard treatment for Obsessive-Compulsive Disorder (OCD). However, a large treatment gap exists, particularly for individuals who do not meet diagnostic criteria. Virtual reality (VR) has the potential to increase access to exposure-based therapy. **Objectives:** This pilot study aimed to examine the preliminary effects of a single-session VRET intervention among individuals with subclinical contamination-related OCD symptoms, and to investigate participant experience and acceptability. **Methods:** Sixteen individuals ($N = 16$) without a formal OCD diagnosis but reporting heightened fears of toilet contamination completed a single in-lab VRET session comprising two self-paced exposures to a simulated contaminated public toilet. Anxiety, affect, OCD symptoms, VR sickness, acceptability, presence, and plausibility were assessed. **Results:** VRET elicited statistically significant variation in anxiety across time points within both exposures (Exposure 1: $\chi^2 = 49.48$, $p < .001$, $W = 0.60$; Exposure 2: $F(1, 15) = 194.39$, $p < .001$, partial $\eta^2 = 0.77$). Contamination symptom scores did not differ significantly between baseline ($M = 5.75$, $SD = 3.51$) and one-month follow-up ($M = 4.45$, $SD = 2.37$; $t(235.85) = 1.52$, $p = .13$), though a large effect size was observed (Hedges' $g = 0.89$, small-sample corrected). Usability was rated above average on the System Usability Scale (SUS) ($M = 69.50$, $SD = 13.70$), and only one participant reported VR sickness. **Conclusions:** A single session of VRET successfully elicited anxiety responses consistent with therapeutic exposure but did not produce significant contamination symptom reduction at one-month follow-up. These findings provide early-phase evidence that VRET is an acceptable and technically feasible delivery modality for subclinical contamination OCD, while indicating that multiple sessions are likely required for sustained symptom change.

4.1 Introduction

The general context for this study, including an overview of subclinical anxiety, exposure-based therapy, and VRET, is provided in Chapter 1. This introduction focuses on the case-specific literature relevant to contamination-related OCD and the rationale for applying VRET to this population.

Obsessive-Compulsive Disorder (OCD) is a disorder characterized by intrusive thoughts, images, or urges, which are distressing and often result in repetitive physical or mental acts that the individual feels driven to perform to temporarily alleviate their distress (Rasmussen & Eisen, 1992). It is associated with income loss, decreased quality of life, and substantial economic burden (Kochar et al., 2023; Veale & Roberts, 2014). According to the National Comorbidity Survey Replication, the lifetime prevalence of OCD is approximately 2.3% (Kessler et al., 2012), though this is thought to be an underestimate due to the stigma often experienced by those with OCD, leading to under-reporting of symptoms (Brady et al., 2010). The most widespread dimension experienced by people with OCD concerns contamination/washing, with up to 50% of people with OCD reporting contamination-related symptoms (Rasmussen & Eisen, 1992). These fears often manifest as persistent and intrusive thoughts about being contaminated by germs, dirt, or other harmful substances (Rasmussen & Eisen, 1992), and typically drive compulsive washing or cleaning behaviors, which the individual performs repeatedly to reduce anxiety and prevent perceived contamination (Rachman, 2006). This cycle of obsessive fear and ritualistic behavior can significantly interfere with daily functioning and overall quality of life.

The prevalence of contamination-related OCD has increased since the COVID-19 pandemic (Guzick et al., 2021). Similarly, symptoms related to fear of contamination have also increased in non-diagnosed populations (Guzick et al., 2021), though it remains to be seen if they will remain elevated. People with mild or undiagnosed OCD symptoms are often overlooked in treatment and research, despite evidence demonstrating that conditions falling below diagnostic cut-offs for anxiety-related disorders still have considerable clinical significance, and these early signs can often predict meeting full diagnostic criteria for OCD in the future (Angst et al., 1997; Bjelland et al., 2009; Fullana et al., 2009). This could be due to reasons such as not meeting the criteria for severity of symptoms, recurrence, presence of obsessions without compulsions, insufficient time consumption, or not causing significant day-to-day impairment. Undiagnosed individuals may include those who meet the criteria for diagnosis but haven't sought or had the chance to be diagnosed, as well as those who do not meet diagnostic criteria (also called subclinical or subdiagnostic symptoms, but referred to in the current paper as not meeting diagnostic criteria). As symptoms occur on a continuum (Abramowitz et al., 2014), research into symptoms that do not meet diagnostic criteria is of clinical value. Symptoms of anxiety-related disorders, including OCD, exhibit significant comorbidity and sequential comorbidity with each other, even at levels below clinical threshold (Haller et al., 2014; Ströhle et al., 2018). Gaining a deeper understanding of OCD symptoms below diagnostic threshold could pave the way for early intervention, reducing the risk of progression to clinical diagnosis.

4.1.1 Traditional Treatment

The traditional first-line gold-standard treatment for OCD is CBT incorporating Exposure and Response Prevention ('Clinical Guideline 31', 2005), which is considered to be a key active ingredient of this treatment. Exposure-based therapy involves confronting a fear-provoking stimulus in a controlled environment, enabling anxiety habituation and/or belief disconfirmation. Its effectiveness as an intervention for fear and anxiety has been well-documented (Abramowitz, 1996; Norton & Price, 2007). Nevertheless, exposure-based therapy is not available to everyone. The majority of people with OCD cannot access evidence-based treatment (Young et al., 2008). Even among those with access to treatment, delays are common, with the average untreated illness lasting over seven years (Perris et al., 2023). These delays are concerning, as longer durations of untreated illness are associated with poorer treatment outcomes (Cipolla et al., 2024) and spontaneous remission is rare in OCD (Burchi et al., 2018). Hurdles to receiving treatment include cost, finding a relevant clinician, and taking time off from school/work for multiple sessions (Conroy et al., 2020). Thus, new intervention solutions are necessary to effectively address these evolving challenges.

4.1.2 Virtual Reality Delivered Exposure-Based Therapy

Digital exposure therapy offers a promising solution to treatment access barriers, providing benefits such as scalability, personalization, and a lower refusal rate compared to traditional exposure-based therapy, suggesting individuals may be more open to it (Felnhofer et al., 2025; Garcia-Palacios et al., 2007; Kothgassner & Felnhofer, 2020). VR is an immersive technology in which a participant experiences and engages with a customized virtual environment other than the external physical environment around them (Gigante, 1993). It has been successfully used to deliver therapy for various conditions such as PTSD, addiction, eating disorders, and acute and chronic pain, as well as for many anxiety-related disorders, such as Generalized Anxiety Disorder, Social Anxiety Disorder, and numerous phobias (Maples-Keller et al., 2017).

Meta-analyses suggest that VRET (also known as VRE) is effective for various anxiety-related disorders and is not inferior to traditional in vivo exposure therapy (Carl et al., 2019; Powers & Emmelkamp, 2008). Due to its potential to encourage realistic behavior in the virtual environment, it is believed that the plausibility and sense of physical presence (i.e., being physically present and immersed) in the VR environment enhance engagement, making exposure therapy more effective (Slater, 2009). Additionally, the documented lower refusal rate may be especially beneficial for the treatment of OCD, due to its typical high refusal and drop-out rates (Leeuwerik et al., 2019; Ong et al., 2016). VRET can be conducted in a clinical setting administered by a clinician or self-administered at home. This flexibility enables individuals to receive treatment without necessarily needing to take time off work or school for travel.

Nevertheless, VRET is not without its limitations. Individuals may experience VR sickness (also called cybersickness), which presents as dizziness, nausea, and other similar motion-sickness related symptoms. While accessibility is currently

a challenge for VRET, as VR technology is still in early stages of adoption by the general public, the global VR market is forecast to hit $103 billion USD by 2027 ('Virtual Reality Market Size, Share, Analysis Report', 2025). The hope is that advancements will make it increasingly accessible–potentially even more so than traditional treatment. Developing an optimal protocol for its operation and implementation to maximize effectiveness and safety remains a crucial challenge that still needs to be addressed.

Though the advantages of VRET begin to rectify the gap in traditional exposure-based treatment, VRET for OCD symptoms is under-explored. Since the release of commercial HMD VR equipment, only four studies on the use of HMD VRET for OCD that involve multiple participants and rely on an exclusive exposure protocol have been published (Cullen, Dowling, Segrave, Carter & Yücel, 2021; Fajnerová et al., 2023; Inozu et al., 2020, 2021).

VR environments designed for exposure-based therapy have been validated in their ability to provoke OCD-relevant distress and compulsive behaviors, yet some findings (i.e., Fajnerová et al., 2023) suggest they may not consistently sustain anxiety levels post-exposure, which is a critical component of fear extinction. However, an earlier study (Inozu et al., 2020) suggested that repeated VR exposure can reduce contamination-related distress, demonstrating its potential as an intervention. Research in comparisons between VRET and in vivo exposure also indicate that VR can provoke similar anxiety responses during exposure, but protocol standardization and long-term effectiveness remain unresolved (Cullen, Dowling, Segrave, Carter & Yücel, 2021). Additionally, while VR has been shown to effectively provoke contamination-related anxiety and disgust, its impact on symptom reduction has not been fully examined, limiting its clinical applicability (Inozu et al., 2021). These gaps highlight the need for systematic, carefully controlled VRET research that explores its preliminary effects on anxiety induction, symptom reduction, and participant acceptability.

Early studies on VRET for contamination fear (e.g., Inozu et al., 2020, 2021) established proof of concept but faced significant limitations. Variability in session lengths, number of sessions, and VR scenario content hindered protocol standardization, limiting the clinical relevance and reproducibility of findings (Inozu et al., 2020). Moreover, previous studies (Inozu et al., 2020, 2021) offered limited exploration of user experience, such as how individuals perceive and respond to VR interventions, usability of the program, or whether the VRET application was deemed acceptable by participants as an intervention.

4.1.3 Aims and Objectives

Standard CBT incorporating ERP for OCD typically involves between 12 and 20 sessions in clinical practice ('Clinical Guideline 31', 2005), with session frequency and duration varying according to symptom severity and treatment setting. In the context of VRET specifically, existing studies have ranged from a single session to eight sessions, as documented in Chapter 2. A single-session design was selected for the present pilot study for two reasons. First, it is consistent with the early-phase feasibility evaluation framework adopted in this thesis, where the primary goal is to assess whether the intervention can elicit the anxiety responses

required for exposure and whether it is acceptable to participants, rather than to test sustained symptom reduction. Second, single-session designs have been used in prior VRET feasibility studies and have been shown to produce measurable effects (Farrell et al., 2021; Inozu et al., 2021; Kahlon et al., 2019), supporting their use as an initial test of intervention viability. The limitations of a single-session design for symptom reduction are acknowledged and discussed accordingly.

To address limitations of prior studies, the present small-scale pilot study aims to examine the outcomes of a single-session intervention for individuals with contamination-related OCD symptoms and investigate user experience with modern HMD VR. We sought to assess the effectiveness of the VRET intervention in reducing OCD symptoms by comparing them to baseline levels and tracking changes over time, including immediate effects on contamination fear severity and outcomes at a one-month follow-up. The present study sought to address the variability found in earlier research by utilizing a standardized protocol with two identical exposures within a single session, modeled after Inozu et al. (2021), Schleider et al. (2019), and Schleider and Beidas (2022), ensuring consistent conditions for all participants and enhancing the reliability of the findings. Additionally, by studying participant experience, including acceptability, VR sickness, and feedback for potential improvements, we aimed to advance understanding of the usability of VRET and inform future intervention design. As no prior studies have focused on this group, we did not formulate specific hypotheses. Instead, we explored the following research questions: (1) What are the preliminary effects of a single-session VRET intervention for contamination-related OCD symptoms? (2) Does this intervention effectively induce anxiety to facilitate exposure? (3) How do participants rate their experience of the VRET, and do they find it acceptable as an intervention?

4.2 Methods

4.2.1 Participants

Participants were recruited via Instagram advertisements and posters placed around the main campus of Imperial College London, directing them to an online screening survey on Qualtrics. The advertisements and posters inquired if potential participants found public toilets stressful and invited them to participate in a VR study exploring discomfort around contamination. Participants were required to be 18 years or older English speakers with contamination concerns. To capture a full range of contamination-related anxiety, these concerns were defined as either a score greater than 0 on the contamination subscale of the OCI-R or a response of 3, 4, or 5 (indicating "sometimes," "often," or "always") to at least one of the following questions/statements constructed for the purposes of this study: (1) "I experience anxiety or distress when I see a dirty toilet," (2) "How often do you find yourself *avoiding* public toilets due to fear or worry that they might be too dirty?", and (3) "How often do you find yourself *unable to use* public toilets due to fear or worry that they might be too dirty?"

Exclusion criteria included reporting any condition precluding adherence to the measurement protocol (such as difficulty reading or writing), any uncorrec-

ted visual and/or auditory impairment affecting full participation in VR (use of corrective lenses or hearing aids was not a criterion for exclusion), current or past diagnosis of OCD (to target below threshold OCD symptoms), current or past treatment for OCD (including psychological and pharmacological therapies), presence or history of epilepsy, and history of severe motion sickness or dizziness. Participants were also excluded if they self-reported currently taking medication that affected heart-rate, such as benzodiazepines.

A total of 48 individuals completed the online screening survey. Of these, 6 were excluded at screening, primarily due to self-reported use of medication that could affect heart rate or anxiety responding and self-reported current or past treatment for OCD. The remaining 42 individuals met eligibility criteria and were invited to participate, of whom 18 scheduled and attended the in-lab session. Data from two participants were excluded due to technical difficulties with the VR hardware, leaving 16 participants in the final analysis. An a priori power analysis was conducted to estimate the required sample size; full details are provided in the Data Analysis section.

4.2.2 Procedure

Participants who met the inclusion criteria and consented to take part in the study were invited to an in-lab session where they were given an online Qualtrics survey to collect baseline information on their OCD symptoms and factors that may influence their levels of anxiety (e.g., medication taken, exercise today, illness, etc.). Participants were then given a brief information sheet about exposure therapy and read a short script providing the context to the VR scenario they would experience shortly. Before entering the VR environment, participants were asked to select the skin color of their avatar. This was done to enhance the experience of embodiment in the virtual environment. Participants then experienced two identical self-paced VR exposures and viewed a short neutral video between exposure sessions. Participants were asked to rank their anxiety (Subjective Units of Distress Scale (SUDS)) four times during each exposure. They reported on their affect (Positive and Negative Affect Schedule (PANAS)) before, between, and after these VR sessions. They were then asked about VR presence and plausibility, with additional repeated measures taken on affect. One month later, an online follow-up survey was emailed to participants to assess OCD symptoms, attitudes relating to contamination, and positive and negative affect.

All participants who completed the in-lab session and one-month follow-up survey were entered into a raffle to win a £30 Amazon e-voucher.

Ethics approval was granted by the Imperial College Research Governance and Integrity Team (Reference number: 22IC7615).

4.2.3 Measures

Demographics. Participants self-reported age, sex, and whether their gender identity matched their sex assigned at birth. They were also asked to self-report variables that could impact anxiety on the day of testing, including caffeine intake, exercise, any medication taken that day, and current illness. Each was

assessed as a binary yes/no item, with an optional free-text field available for participants to provide additional detail if they responded yes. These variables were collected to characterize the sample on the day of testing and to identify any participants whose physiological or anxiety responses may have been atypically influenced by same-day factors. They were not used as covariates in the primary analyses, as the small sample size precluded meaningful covariate adjustment.

Psychiatric Diagnoses. Participants self-reported any past or current psychiatric diagnoses.

OCD. Participants reported contamination-featured OCD symptoms using the Washing subscale of the OCI-R at baseline ($\alpha = 0.83$, $SE = 0$) and at one-month follow-up ($\alpha = 0.59$, $SE = 0.02$). The OCI-R is a widely used self-report measure of OCD symptoms, comprising 18 items that assess symptoms across six subscales (Foa et al., 2002). Each item is rated on a 5-point Likert scale ranging from 0 ("not at all") to 4 ("extremely"). The contamination subscale includes 3 items, with a total score range of 0 to 12, where higher scores indicate greater contamination-related distress.

Anxiety & Affect. Momentary anxiety was measured using the one-item SUDS on a 11-point Likert scale administered verbally during each VR exposure (Wolpe, 2018). To measure positive and negative affect, the short-form of the PANAS was administered at baseline ($\alpha = 0.78$, $SE < 0.01$), after the first VR exposure ($\alpha = 0.85$, $SE = 0$), after the break between exposure sessions ($\alpha = 0.89$, $SE = 0$), and after the second VR exposure ($\alpha = 0.92$, $SE = 0$). The PANAS consists of two scales (one for positive affect and one for negative affect), both on a 5-point Likert scale (Thompson, 2007).

Usability, Acceptability, & VR Experience. VR presence refers to the subjective sense of physically being in the virtual environment, and plausibility refers to the degree to which the virtual environment evoked anxiety comparable to a real or imagined equivalent scenario (Slater, 2009). Both were measured by two items each adapted from Slater (2009). To measure plausibility, participants compared their anxiety in the virtual environment to 1) a real public toilet and 2) an imagined public toilet, on a 5-point Likert scale where 1 is much more anxious in VR and 5 is much more anxious in the real or imagined scenario. VR sickness was measured using the Simulator Sickness Questionnaire (SSQ) ($\alpha = 0.86$ at baseline, $\alpha = 0.77$ post-intervention) on a 4-point Likert scale (Kennedy et al., 1993). To assess usability as a component of acceptability, participants completed the SUS ($\alpha = 0.81$, $SE < 0.01$), a validated 10-item scale on a 5-point Likert scale (Brooke, 1995). While the SUS does not provide a direct psychometric assessment of acceptability, it was included as a pragmatic, quantifiable proxy for usability-related components of acceptability, consistent with digital health research (Collins-Pisano et al., 2024; Isaacs et al., 2023) and the Theoretical Framework of Acceptability (Sekhon et al., 2017). To capture broader dimensions of acceptability beyond usability, open-ended questions were also included, such as "How did you feel while you were taking part in the virtual reality experience?" and "In your opinion, is there anything that could have been done differently to improve the software or create a better experience?"

4.2.4 VRET Intervention

The VRET intervention was designed to function as a single-session exposure-based protocol consistent with ERP principles for contamination-related OCD. Prior to entering the VR environment, participants received a brief information sheet explaining the rationale for exposure therapy and a standardized verbal script contextualizing the VR scenario. This psychoeducation was intentionally brief to avoid extensive cognitive preparation that could function as a safety behavior, consistent with inhibitory learning principles (Craske et al., 2014). The VR environment and its exposure sequence were developed by XRHealth's clinical team and were not designed by the research team. The sequence of contamination-relevant tasks within the environment progressed from lower to higher contact with contaminating elements: entering the public toilet, opening the cubicle door, touching the wall, lowering the toilet lid, flushing the toilet, sitting on the toilet, taking toilet paper, touching the toilet brush, and finally washing hands. This ordering is broadly consistent with a graduated exposure hierarchy, with the highest-contact tasks (e.g., touching the toilet brush) representing the most anxiety-provoking stimuli. However, the specific rationale and design decisions underlying this hierarchy were made by XRHealth and are not fully documented in the published literature. Participants completed all tasks in sequence at their own self-determined pace, consistent with self-paced exposure protocols (Inozu et al., 2021). Response prevention was implemented by withholding hand-washing until the end of the exposure sequence. Participants were not permitted to wash their hands in VR until they had completed all preceding contamination tasks, and the hand-washing step was positioned as the final action of each exposure rather than a freely available coping behavior. This is consistent with standard ERP practice, in which compulsive responses are delayed or prevented to allow anxiety to peak and begin to subside, thereby facilitating inhibitory learning (Craske et al., 2014; 'Clinical Guideline 31', 2005). No formal cognitive restructuring or safety behaviors were incorporated into the protocol. A researcher was present throughout the session to manage the technical aspects of the VR system and administer the SUDS prompts, but did not provide therapeutic coaching or in-session guidance. This reflects the self-guided nature of the protocol and its intended use as a scalable, low-supervision intervention.

4.2.5 Equipment & Environment

We used Amelia by XR Health's ('XRHealth', n.d.) public toilet VR environment, which depicts a contaminated public toilet in a subway area (Figure 4.1). The scenario begins with the participant standing outside the door of a public toilet. The participant sees other individuals by the cubicles and the sink upon entering. The participant is able to enter the cubicle in front of them and interact with the toilet-related elements (e.g., toilet lid, toilet paper, toilet brush), and can sit down on the toilet (the participant can simultaneously sit in a chair in the real world to mirror their position in VR). The participant is then placed in front of the sink and able to wash their hands in the virtual scenario. The software was run on PICO G2 HMD VR headsets.

The VR environments are controlled through Amelia by XRHealth's online platform, where the following actions can be taken: open the entrance door, open the cubicle door, touch the wall while standing inside the cubicle, lower the toilet lid, flush the toilet, touch the wall while sitting on the toilet, take toilet paper, touch the toilet brush, and wash hands. In this study, participants completed the actions in the given order at their own pace. When asked to sit on the virtual toilet, a real-life chair was provided to heighten the sense of immersiveness in the virtual environment.

Figure 4.1. Screenshot of the VR Environment Depicting a Dirty Public Toilet

4.2.6 Data Analysis

Previous meta-analyses of VRET for anxiety-related disorders reported effect sizes ranging from $d = 0.88$ to $d = 1.08$ (Carl et al., 2019; Powers & Emmelkamp, 2008). These estimates are drawn from meta-analyses spanning multiple anxiety disorders and a range of protocol designs, including multi-session interventions and both clinical and non-clinical populations. They are therefore not directly comparable to the present single-session pilot targeting subclinical OCD symptoms. However, in the absence of OCD-specific or single-session VRET effect size data at the time of study design, these meta-analytic estimates represented the best available benchmarks for an a priori power calculation. Their use is acknowledged as a limitation of the sample size estimation. With an alpha of 0.05 and a power of 0.95, a sample size of 20 participants would be needed to detect a $d = 0.88$ effect size and 14 participants would be needed to detect a $d = 1.08$, using a two-tailed Wilcoxon signed-rank test for a one-sample case. Given the a priori power analysis, feasibility of recruitment, and the limited availability of condition-specific effect size data, we aimed to recruit 15 to 30 participants.

The study was preregistered on AsPredicted (accessible at https://aspredicted.org/r2bh-rncc.pdf). An additional aim of exploring user experience and acceptability was added after the preregistration. Three measures included in the preregistration were subsequently dropped from analyses: the Patient Reported Outcomes Measurement Information System - Anxiety (PROMIS anxiety), the Work and Social Adjustment Scale (WSAS), and the Distress Tolerance Scale (DTS). These measures were included in the original preregistration to capture a broader range of potential outcomes during the early study design phase, when a wider exploratory scope was envisaged. Following preregistration, the study objectives were refined to focus more specifically on contamination symptom change, anxiety induction, and participant experience. At that stage, these three measures were determined to have limited alignment with the primary research questions: the PROMIS anxiety as a general anxiety measure that overlapped in scope with the contamination-specific OCI-R without adding specificity to the primary symptom domain (Pilkonis et al., 2011), the WSAS as a functional impairment measure assessing a timeframe not addressable by a single exposure session (Mundt et al., 2002), and the DTS as a stable dispositional trait measure (Simons & Gaher, 2005) unlikely to shift within a single session. Their removal was a preregistered deviation and is acknowledged as a transparency consideration. Physiological data were not analyzed in the current study.

Statistical analyses were performed in R. Data was analyzed to explore symptom outcomes, participant experience, and potential outcome predictors. To examine symptom outcomes, statistical analyses were selected based on normality assessments (Shapiro-Wilk tests). Repeated measures ANOVAs were conducted for variables meeting assumptions of normality (positive affect), while Friedman tests, a non-parametric alternative, were used for variables violating these assumptions (negative affect and anxiety levels). Paired t-tests were additionally performed to compare pre- and post-intervention scores for contamination symptoms, which met normality criteria. Effect size calculations were conducted to investigate magnitude of changes. To examine participant experience, descriptive

data for virtual sense of presence and plausibility, descriptive data for intervention acceptability, frequency of item endorsement on the SUS, and open-answer participant feedback for areas of intervention improvement were studied.

The rate of missing data was 5.47%. It was found to be a combination of Missing at Random (participants who did not take the follow-up survey) and Missing Completely at Random (participants accidentally skipping a question without any distinct pattern) and was addressed using Multiple Imputations with Chained Equations (MICE) with random forest. Unless otherwise specified, pooling was conducted on all analyses using Ruben's Rules. Statistical significance was defined at $p < 0.05$.

4.3 Results

The sample comprised 6 females, 9 males, and 1 individual who preferred not to say; 87.5% of participants reported a gender identity that matched their sex assigned at birth. Participants were aged 18–32 ($M = 21.75$, $SD = 3.86$). A comprehensive summary of participant characteristics and baseline outcome scores is provided in Table 4.1.

Table 4.1. Participant Characteristics and Baseline Outcome Scores

Characteristic	Value
Demographics	
N	16
Age, *M* (*SD*)	21.75 (3.86)
Age range	18–32
Female, *n* (%)	6 (37.50)
Male, *n* (%)	9 (56.25)
Preferred not to say, *n* (%)	1 (6.25)
Gender matches sex at birth, *n* (%)	14 (87.50)
Prior VR experience, *n* (%)	4 (25.00)
Baseline Outcome Scores	
Contamination symptoms (OCI-R), *M* (*SD*)	5.75 (3.51)
Contamination symptoms (OCI-R), range	0–11
Perceived OCD 1[a], *M* (*SD*)	3.92 (1.07)
Perceived OCD 2[b], *M* (*SD*)	3.49 (1.09)
Perceived OCD 3[c], *M* (*SD*)	3.19 (0.91)

Note. Baseline outcome scores are pooled across 5 imputed datasets. Demographic counts represent pre-imputation values.

[a] "I experience anxiety or distress when I see a dirty toilet." Rated on a 5-point scale (1 = Never, 5 = Always).

[b] "How often do you find yourself *avoiding* public toilets for fear or worry that they might be too dirty?" Rated on a 5-point scale (1 = Never, 5 = Always).

[c] "How often do you find yourself *unable to use* public toilets for fear or worry that they might be too dirty?" Rated on a 5-point scale (1 = Never, 5 = Always).

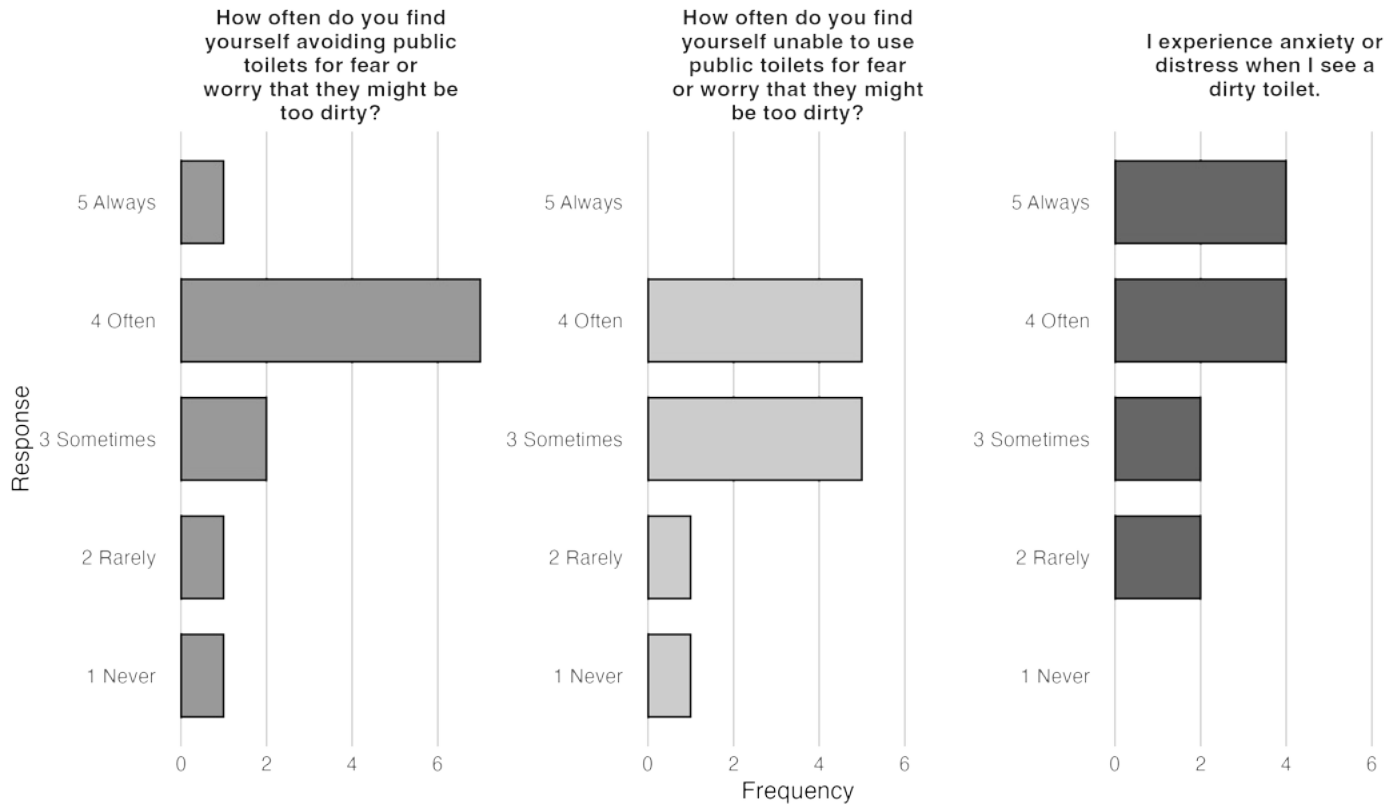
Baseline contamination symptoms (as measured by the contamination subscale on the OCI-R) ranged from 0-11 ($M = 5.75$, $SD = 3.51$), out of a max score of 12. Perceived contamination OCD symptoms at baseline are shown in Figure 4.2. 4 participants reported having prior VR experience. Table 4.2 displays descriptive statistics for main study variables. Correlations between primary variables of interest were examined using Spearman's ρ with False Discovery Rate correction and are presented in Table A.1 in the Appendix. After correction, only one correlation was statistically significant: average anxiety during Exposure 1 and average anxiety during Exposure 2 were strongly positively correlated ($\rho = .91$, $p < .001$), which is expected given that both measures reflect anxiety responses to identical stimuli within the same session. All other correlations were non-significant after FDR correction, indicating no unexpected associations among the primary study variables.

Table 4.2. Descriptive Statistics for Main Study Variables

Variable	M	SD
Baseline contamination score	5.75	3.51
Perceived OCD 1	3.92	1.07
Perceived OCD 2	3.49	1.09
Perceived OCD 3	3.19	0.91
Presence 1	4.62	1.78
Presence 2	4.56	1.59
Plausibility 1	4.19	0.91
Plausibility 2	3.56	1.03
System Usability Scale (SUS)	69.50	13.70
Contamination score at follow-up	4.45	2.37

Note. Values are pooled across 5 imputed datasets. Perceived OCD 1 = "I experience anxiety or distress when I see a dirty toilet"; Perceived OCD 2 = "How often do you find yourself *avoiding* public toilets for fear or worry that they might be too dirty?"; Perceived OCD 3 = "How often do you find yourself *unable to use* public toilets for fear or worry that they might be too dirty?"; Presence 1 = "I had the sensation of being in the public toilet."; Presence 2 = "I had the sensation that the scenario was really happening."; Plausibility 1 = "Compared to a *real* public toilet, did you feel as uncomfortable and/or anxious in the virtual environment?"; Plausibility 2 = "Take a second to imagine that you are in a public toilet. Compared to this *imagined* public toilet, did you feel as uncomfortable and/or anxious in the virtual environment?"

Figure 4.2. Frequencies of Perceived Contamination Fear



Note. This table represents raw data. 2 participants did not complete these questions.

4.3.1 Symptom and Anxiety Outcomes

The Friedman test for negative affect indicated a statistically significant difference across session time points ($\chi^2 = 23.83$, $p < .001$, $W = 0.29$). The repeated measures ANOVA for positive affect revealed a statistically significant difference during the VRET session, ($F(4.04, 15) = 99.96$, $p < .001$, partial $\eta^2 = 0.96$). For anxiety in the first VR exposure, the Friedman Test indicated a statistically significant difference in SUDS scores across time points ($\chi^2 = 49.48$, $p < .001$, $W = 0.60$). For the 2nd VR exposure, a repeated measures ANOVA indicated a significant difference in SUDS scores again ($F(1, 15) = 194.39$, $p < .001$), with a large effect size (partial $\eta^2 = 0.77$).

Figure 4.3 displays a graph of average anxiety levels over both VR exposures, including the four tasks that the participants experienced. Anxiety levels rose from baseline as participants interacted with the contaminated-looking VR environment and declined after exposure when they performed virtual hand-washing. Highest levels of anxiety were reported when participants were engaging most directly with the contaminated environment (e.g., touching the dirty-looking stall wall or toilet brush).

Figure 4.3. Anxiety During Both VR Exposures

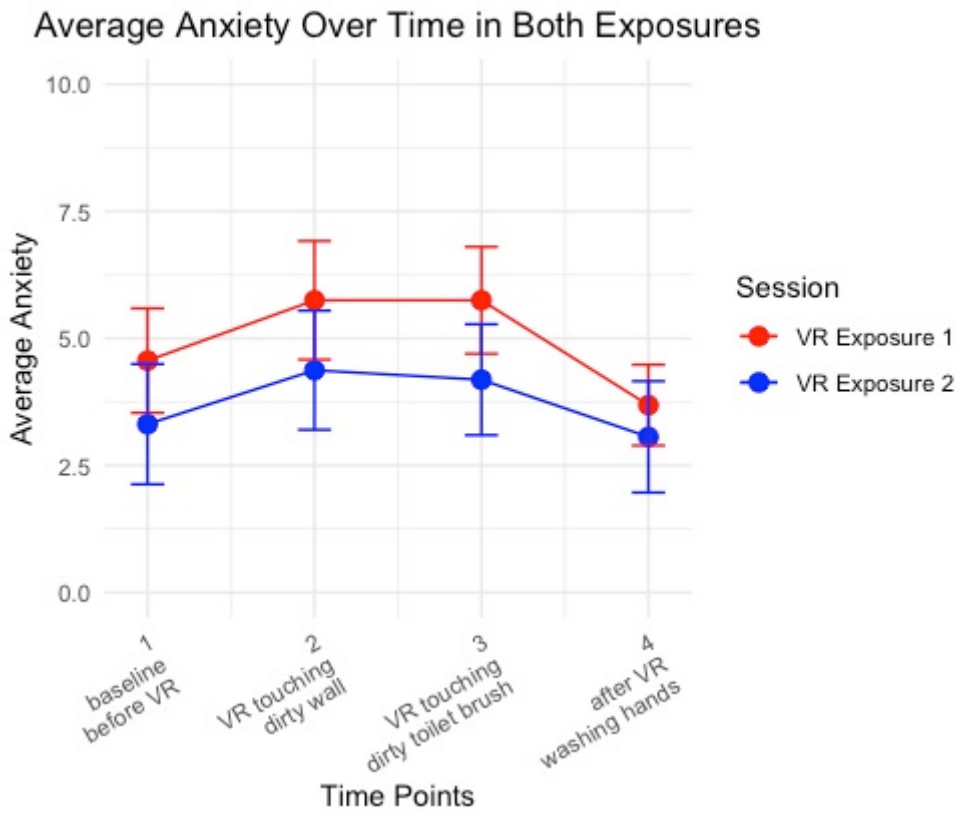
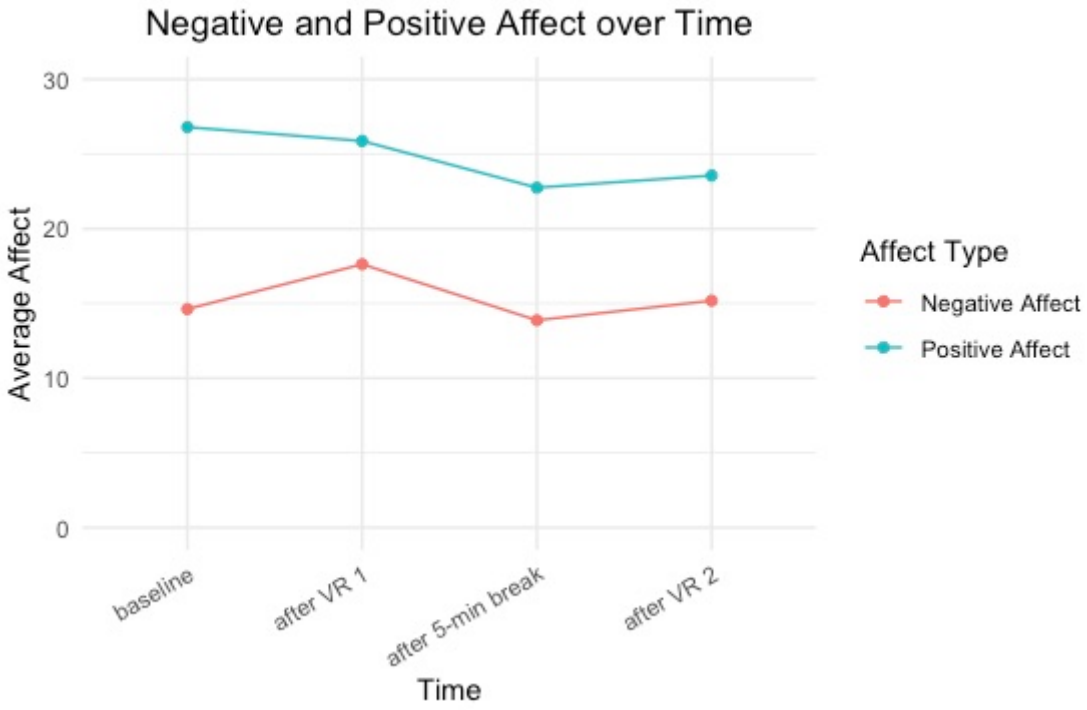


Figure 4.4 illustrates average negative and positive affect over time, showing an increase in negative affect from baseline after the first VR exposure, a return to baseline following a 5-minute break, and another rise after the second VR exposure. Positive affect declined after the 5-minute break, with a slight decrease

from baseline to the end of the first VR exposure, followed by a small increase from the break to the end of the second VR exposure.

Figure 4.4. Average Positive and Negative Affect Across Both VR Exposures

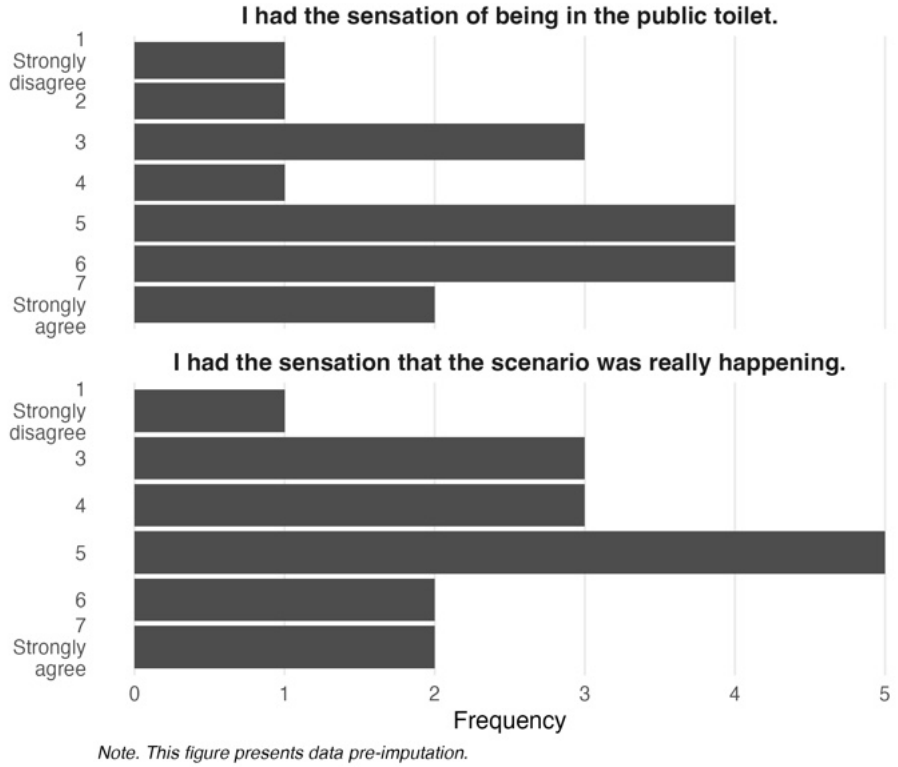


To investigate the preliminary effects of VRET on OCD symptoms, a paired t-test was conducted comparing baseline contamination scores ($M = 5.75$, $SD = 3.51$) to one-month follow-up scores ($M = 4.45$, $SD = 2.37$). The results were not statistically significant ($t(235.85) = 1.52$, $p = .13$, 95% CI [-0.38, 2.98]). The high degrees of freedom reflect minimal between-imputation variability, increasing confidence in the pooled estimate. Hedges' g was calculated to assess the magnitude of change, applying a small-sample correction appropriate for $N < 20$ (Hedges, 1981). For contamination symptoms, comparing baseline to one-month follow-up, a large effect size was observed ($g = 0.89$), indicating a meaningful reduction in scores despite the absence of statistical significance, likely reflecting insufficient statistical power given the small sample. For affect, effect sizes were calculated comparing baseline to immediately post-intervention scores: a large effect size in the expected direction was observed for negative affect ($g = -0.88$), indicating a reduction, and a large effect size was observed for positive affect ($g = 1.84$), indicating an increase. These effect sizes should be interpreted with caution given the small sample size and absence of a control group; they represent preliminary signals rather than confirmed effects.

4.3.2 Participant Experience

To assess participants' perception of the virtual environment, VR presence (sense of physical immersion and engagement) and plausibility were examined.

Figure 4.5. Frequencies of Endorsement for Presence in the Virtual Environment

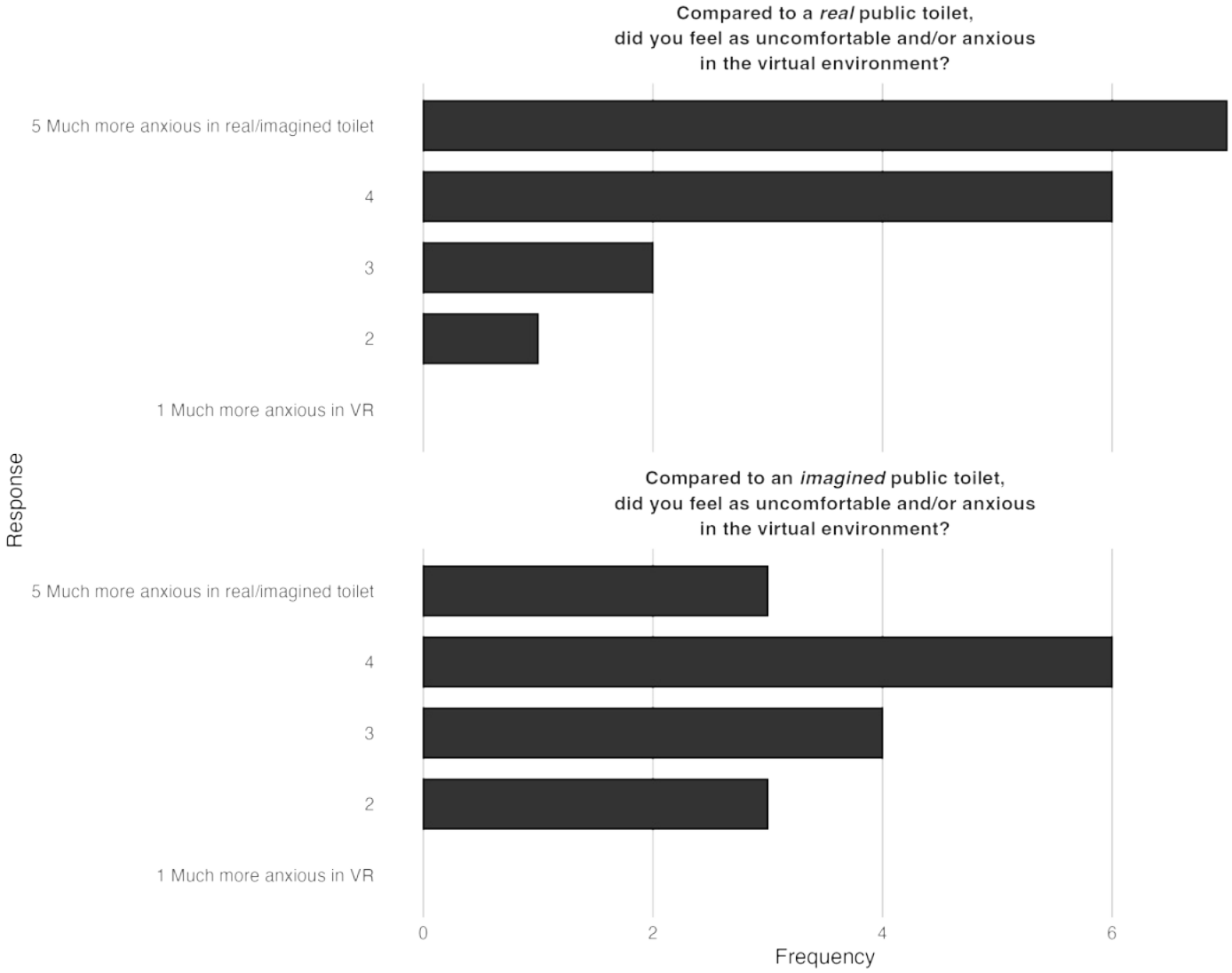


Note. This figure presents data pre-imputation.

Figure 4.5 presents participant responses to questions on virtual presence. Mean presence scores were above the scale midpoint for both items (Presence 1: $M = 4.62$, $SD = 1.78$; Presence 2: $M = 4.56$, $SD = 1.59$, on a 5-point scale), indicating an overall stronger-than-neutral sense of being present in the virtual environment.

Plausibility scores are shown in Figure 4.6. Mean plausibility ratings were above the scale midpoint when comparing the VR environment to a real public toilet (Plausibility 1: $M = 4.19$, $SD = 0.91$) and near the midpoint when comparing to an imagined public toilet (Plausibility 2: $M = 3.56$, $SD = 1.03$, on a 5-point scale where higher scores indicate greater anxiety in the real or imagined scenario than in VR). This suggests that on average the virtual environment elicited anxiety broadly comparable to a real scenario and somewhat more anxiety than an imagined scenario, though responses varied across participants.

Figure 4.6. Frequencies of Endorsement for Plausibility in the Virtual Environment



Note. This figure presents data pre-imputation.

Participants reported high levels of acceptability for the VRET intervention. On the SUS, participants scored between 30.0 and 87.5, with a mean of 69.50 ($SD = 13.70$), where a score of 68 is typically considered average and acceptable Hyzy et al., 2022. Item-level endorsement frequencies on the SUS indicated that the majority of participants agreed or strongly agreed that the system was easy to use, that they felt confident using it, that they would not need technical support to use it, and that most people would learn to use it quickly (see Table A.2 in the Appendix for full item endorsement data). A participant described using the intervention as "...an enjoyable, fun experience and a good way for exposure therapy without causing too much distress." Another participant wrote, "...overall it was very good and well instructed. I can see how multiple sessions of this kind could help with this issue as it wouldn't feel so daunting to enter contaminated

places of this kind." Complete participant feedback is listed in Table A.3 in the Appendix.

Only 1 participant reported VR sickness after the session. Table 4.3 examines VR sickness scores as measured by the SSQ after each exposure. Disorientation was the highest reported symptom. Total VR sickness was much higher after the second ($M = 105.89$, $SD = 13.64$) than after the first exposure ($M = 25.25$, $SD = 25.13$). Total score for VR sickness ranged from 0 to 78.54 for post first exposure and 78.54 to 130.90 for post second exposure.

Table 4.3. Simulator Sickness Questionnaire Scores After Each Exposure Session

	Nausea	**Oculomotor**	**Disorientation**	**Total Score**
	M, Mdn(SD)	M, Mdn(SD)	M, Mdn(SD)	M, Mdn(SD)
After Exposure #1	21.46, 9.54 (23.24)	23.21, 18.95 (21.88)	20.01, 13.92 (22.14)	25.25, 20.57 (25.13)
After Exposure #2	88.84, 85.86 (16.23)	75.33, 75.80 (10.16)	126.15, 125.28 (22.43)	105.89, 108.46 (13.64)

Participants suggested several areas of improvement to the VR environment. One participant mentioned that "...the avatar's body blocked the view of some elements so perhaps adjusting the dimensions of the avatar could enhance the viewing experience." Participants also mentioned "somehow trying to recreate the smell, though that might be quite gross," and "...maybe if the environment had been changing more, like someone banging on the door or sounds of other people defecating, it would've felt more real. I think those are the kind of experiences that the VR might actually make me more resilient to." Participants frequently expressed a desire for changes in the avatar's body dimensions (i.e., the amount of body seen from the first person avatar perspective) to allow for a clearer view inside the toilet bowl, as well as multi-sensory enhancements (e.g., sounds and smells) to increase plausibility and immersion. Table A.3 in the Appendix includes a full list of participant feedback.

4.4 Discussion

4.4.1 Key Findings

This study examined the preliminary effects of a VRET application as a single-session intervention for contamination-related OCD symptoms, as well as user experience, including acceptability. The VRET application impacted momentary affect and anxiety both during and immediately after the intervention. However, a single session of the intervention demonstrated no significant difference between pre-intervention baseline and one-month follow-up for contamination symptoms. This suggests that while the intervention successfully increased anxiety, a single session was not associated with symptom reduction after one month. The limited nature of the intervention may not have been sufficient to establish habituation or for habituation to become ingrained in real-life scenarios, and further research is needed to determine therapeutic benefits. Changes in anxiety over time in both

exposures (i.e., increasing from baseline while interacting with the contaminated environment and decreasing after virtual hand-washing at the end of exposure) also demonstrated the contaminated VR environment was capable of eliciting anxiety. Anxiety levels were slightly higher on average during the first exposure compared to the second, which is likely due to the environment habituation by the second exposure. Indeed, participants were more familiar with the environment and the protocol when they engaged in the second VR exposure.

This is further supported by the observed changes in positive and negative affect. Figure 4.4 shows negative affect rising from baseline after the first VR exposure, returning to baseline following the 5-minute break, and increasing again after the second VR exposure. These fluctuations indicate that the break effectively restored participant affect to neutral and reduced the negative affect induced by the exposures. Positive affect decreased after the 5-minute break, with a slight drop from baseline to the end of the first VR exposure and a small increase from the break to the end of the second exposure. This may be attributed to the novelty of the intervention and a sense of relief at the session's conclusion.

Presence scores indicated a moderate sense of immersion (see Section 4.3.2), while plausibility ratings suggested that participants did not find the VR environment overly anxiety-provoking compared to real or imagined public toilet scenarios. Coupled with good acceptability, this suggests a role for VRET as a possible stepping stone in treatment between imagery exercises and in vivo exposure. While the VR environment successfully elicited anxiety, the single-session design may have limited the opportunity for habituation, which is critical for symptom reduction. This is consistent with clinical recommendations for OCD treatment, which typically involve 12 to 20 sessions of CBT incorporating ERP ('Clinical Guideline 31', 2005), and with the broader VRET literature in which multi-session protocols of up to eight sessions have been employed (Cullen, Dowling, Segrave, Carter & Yücel, 2021; Inozu et al., 2020). The present single-session design was therefore not expected to replicate the symptom reduction associated with full treatment courses, and the absence of significant symptom change at one-month follow-up should be interpreted accordingly. This suggests that repeated exposures over multiple sessions may be necessary for VRET to function as a standalone intervention. Given the exploratory, self-paced single-session design, our findings cannot conclusively speak to long-term efficacy, but they do underscore VRET's potential either as a standalone or adjunct intervention, contingent on session structure and target intensity. Participants rated the system's usability above average, felt confident using the intervention, and found it manageable without technical support. This implies that the VRET has the potential to be used independently of live clinical supervision (i.e., as therapy homework between sessions). Additionally, it suggests that individuals with no prior experience with virtual reality may not need extensive technical training before using the program. However, further research across diverse age groups, gender, and technological literacy levels is needed.

Though only one participant reported VR sickness, others experienced related symptoms, such as disorientation and nausea. We believe that VR sickness was minimal due to the limited movement of the participants' avatars. Furthermore, disorientation symptoms were the most commonly endorsed, over nausea or ocu-

lomotor symptoms. This may be due to technical issues like latency, inconsistent frame rates, or unnatural field of view and depth perception. It could also result from participant fatigue (spending too long in VR without breaks to reset proprioception) or inadequate embodiment (not feeling connected to the avatar as their own body).

4.4.2 Comparison with Previous Literature

The finding that a single session of VRET successfully elicited anxiety in participants with subclinical contamination-related OCD is consistent with prior work in clinical populations. Inozu et al. (Inozu et al., 2021) demonstrated that VR contamination environments provoked anxiety and disgust in individuals with high contamination fear, and Cullen et al. (Cullen, Dowling, Segrave, Carter & Yücel, 2021) found that VRET elicited anxiety responses comparable to in vivo exposure in diagnosed OCD patients. The present findings extend these results to a subclinical sample, suggesting that the anxiety-eliciting properties of contamination VR environments generalize beyond clinically diagnosed populations. The pattern of anxiety rising during active contamination tasks and declining toward the end of each exposure is broadly consistent with within-session habituation as described in exposure therapy models (Craske et al., 2014; Foa & Kozak, 1986), though it is acknowledged that the inclusion of virtual hand-washing as the final step of each exposure may have contributed to anxiety reduction through relief rather than pure habituation.

The absence of significant symptom reduction at one-month follow-up is similarly consistent with the mixed picture in the existing literature. Fajnerová et al. (Fajnerová et al., 2023) found that while VRET provoked distress and compulsive behaviors in OCD patients, anxiety levels did not consistently decrease post-exposure, and symptom reduction was not uniformly observed. The present finding of a large effect size ($g = 0.89$) alongside non-significant change reflects the limited power of a small single-session pilot rather than an absence of preliminary signal, and aligns with the broader literature suggesting that multi-session protocols are likely needed for sustained symptom reduction (Cullen, Dowling, Segrave, Carter & Yücel, 2021; Inozu et al., 2020).

Our VR sickness scores after one exposure ($Mdn = 20.57$, $SD = 25.13$) were comparable to those of the healthy control group in Fajnerová et al. (2023), who reported median scores of 21.50 ($SD = 58.08$). This is likely because the participants in this study had symptoms below the clinical threshold, making them more similar to healthy controls than to the diagnosed OCD group in Fajnerová et al. (2023). However, the teleportation movement mechanic used in the VR environment of Fajnerová et al. (2023), which was not used in the current study, likely contributed to higher VR sickness scores.

4.4.3 Limitations

This pilot study is not without limitations. The study's sample size was limited, which could have potentially diminished its generalizability. Nevertheless, it offers valuable preliminary data that will inform future research endeavors. The

broad range of contamination scores (as measured by the contamination subscale on the OCI-R) represents a full spectrum of contamination-related anxiety. However, the inclusion of participants with relatively low contamination scores could have diluted the observed intervention effects, potentially masking significant findings or underestimating the true magnitude of change among individuals with higher baseline symptoms. Nevertheless, a sensitivity analysis for contamination scores was not feasible due to the small sample size. The absence of a control group further limits the interpretation of results by restricting the ability to examine causal inference. There may be alternative explanations for our results, such as expectancy effects or regression to the mean. Another constraint is the lower internal consistency observed for the OCI-R subscale at the one-month follow-up compared to baseline. Since the OCI-R demonstrated strong reliability at baseline, this decline is unlikely due to flaws in the measure itself. Indeed, repeated exposure to tests can affect participant performance, and sample attrition can impact the consistency of measurements, potentially distorting reliability estimates (Singer & Willett, 2003). Furthermore, while measuring contamination symptoms using the OCI-R subscale at the one-month follow-up may present limitations for detecting change following a single-session intervention, prior research has demonstrated that even single-session VRET interventions can produce measurable effects at one month or later (e.g., Farrell et al., 2021; Kahlon et al., 2019). Participant bias is another potential limitation, given the novel nature of the technology and the recruitment method. Specifically, self-selection bias may have led participants to be more motivated to address their contamination-related fears, possibly increasing the perceived effectiveness of the intervention. Additionally, individuals drawn to the pilot study may have had a preexisting interest in VR technology, which could have influenced engagement and overall perception of the intervention, regardless of its direct impact on symptoms. Finally, the sample was insufficiently powered to examine sex as a moderator of treatment response. Future research with larger samples should investigate whether sex is associated with differential outcomes following VRET for contamination-related OCD symptoms.

4.4.4 Strengths

Despite these limitations, our pilot study has several strengths, as it offers a comprehensive analysis by examining both the program's usability and its acceptability as an intervention. Evaluating usability ensures that users can navigate the program effectively, which is crucial for maintaining engagement and optimizing the user experience. In contrast, assessing acceptability illuminates how well the intervention is received by users, indicating its potential for integration into routine clinical practice and enhancing overall treatment adherence. In addition, by incorporating both quantitative study design elements and open-ended questions, we gain a nuanced, multifaceted understanding of critical factors, such as participant perceptions of usability, intervention acceptability, and subjective experiences during VR exposure tasks. Furthermore, rather than focusing solely on OCD symptom reduction, we explore additional dimensions such as anxiety, as well as positive and negative affect. This broader evaluation provides insight

into the emotional processes during exposure, such as the temporary increase in negative affect and recovery during the break, supporting the VRET's ability to provoke and modulate anxiety.

4.4.5 Implications for Research, Policy, and Practice

Although a single VRET session yielded promising exploratory results in our pilot study, it failed to yield lasting effects on contamination symptoms at the one-month follow-up. Therefore, a crucial future direction is to investigate the impact of multi-session interventions. Expanding the intervention to multiple sessions may enhance its effectiveness, promote sustained symptom reduction, and provide deeper insights into the long-term benefits of VR for contamination-related OCD symptoms. Future research should examine variations in session frequency, exposure duration, and the number of exposures per session to optimize treatment effectiveness. Future work should also clarify the optimal positioning of VRET within the exposure therapy hierarchy, whether as a full intervention requiring multiple sessions or as a preparatory step for more intensive in vivo exposures. Additionally, studies should include larger sample sizes and control groups while exploring the role of VR presence and plausibility as potential predictors of treatment outcomes. Future research should build on this pilot by conducting full-scale trials to evaluate efficacy and support broader clinical application.

As VR technology advances, improvements in latency, frame rates, and display resolution continue to enhance the user experience, dramatically reducing VR sickness in users (Stauffert et al., 2020; Tian et al., 2022). However, software and content design must also be enhanced to minimize VR sickness. This can be done through incorporating techniques such as modifying field of view, reducing vection (i.e., the sensation of motion), and further implementing rest frames (i.e., non-movement visual elements in the environment; Tian et al., 2022). All of these techniques can help the user maintain better alignment between visual and vestibular systems. Ongoing research into individual susceptibility to VR sickness (Tian et al., 2022) could help identify those who may benefit from VRET while minimizing the risk of VR-induced discomfort.

Future directions for adjusting the virtual environment's design include enhancing the visual detail of the toilet bowl and incorporating additional sensory modalities, such as sound and smell. Visual contamination of the toilet bowl is likely an important anxiety-provoking stimulus for many individuals with contamination fears. Multi-sensory additions to the environment could range from relatively straightforward implementations, such as integrating spatial audio to simulate the presence and movement of individuals within the public toilets, to more sophisticated approaches leveraging advanced technologies to introduce olfactory stimuli to the virtual environment. While participants in our study highlighted the potential benefits of incorporating smell, it is crucial to carefully consider the use of non-consumer technologies. This could potentially hinder the accessibility, affordability, and scalability of the intervention in real-world applications.

4.4.6 Conclusion

This study aimed to determine whether VRET could effectively induce anxiety as a key component of exposure-based therapy for contamination-related OCD symptoms, while also assessing its acceptability among participants in a small-scale pilot study. Our findings offer preliminary evidence that VR can be a promising medium for exposure therapy, bridging the gap between imagined and in vivo exposure and highlighting its potential as a scalable and accessible treatment tool. The single session did not, however, produce significant contamination symptom reduction at one-month follow-up, consistent with the early-phase, limited-efficacy-testing aims of this pilot and the expectation that sustained symptom change likely requires multiple sessions. Further research is also needed to confirm these preliminary findings within populations with symptoms below clinical threshold and to extend investigations to clinical populations, thereby evaluating the broader applicability and clinical value of VRET as an intervention for individuals with diagnosed OCD. Future studies should investigate the efficacy of multi-session interventions, enhance VR environments to maximize immersion, and conduct long-term assessments to evaluate sustained treatment outcomes. The following chapter reports a second case study examining whether these early-phase findings generalize to a different subclinical anxiety presentation, specifically fear of needles, using a comparable single-session VRET protocol.

5 Case Study II: Virtual Reality Exposure Therapy for Subclinical Fear of Needles & Injection

ABSTRACT

Background: Fear of needles significantly impacts individual and public health by leading many adults to avoid necessary medical procedures, including vaccinations and blood tests. Virtual Reality Exposure-Based Therapy has shown promise as an effective and accessible intervention for anxiety disorders but remains under-explored. **Objectives:** This study aimed to evaluate the preliminary effectiveness and acceptability of a single-session virtual reality intervention targeting fear of needles in adults. **Methods:** A total of 62 adults reporting needle fear were recruited into experimental (n = 32) and online comparison groups (n = 30). The experimental group completed one Virtual Reality Exposure-Based Therapy session, which comprised of two self-paced VR exposures simulating medical needle procedures. Anxiety and affect were assessed at baseline, during, and immediately following virtual reality exposures, and at a one-month follow-up. Acceptability, usability, presence, plausibility, and virtual reality sickness were also measured. **Results:** The intervention elicited statistically significant variation in anxiety across time points within both VR exposures (Friedman tests: $p < .001$ for both exposures) and a statistically significant reduction in anxiety from baseline to post-intervention in the experimental group ($p = .02$). Following the intervention, the experimental group reported significantly lower anxiety when viewing needle images compared to the comparison group ($W = 695.00$, $p = .002$, $r = 0.39$). At one-month follow-up, a statistically significant reduction in symptom severity was observed on the Specific Phobia Questionnaire ($t(31) = 2.24$, $p = .03$), though no significant change was noted on the Medical Fears Survey ($t(31) = 1.39$, $p = .18$) or in life interference ($t(31) = -0.15$, $p = .88$). Usability ratings on the System Usability Scale were above average ($M = 73.36$, $SD = 17.29$; threshold for above-average usability = 68). A subset of participants reported virtual reality sickness symptoms including disorientation and motion sickness. **Conclusions:** A single session of VRET successfully elicited and reduced anxiety during exposure and was rated as acceptable by participants. Symptom reduction at one-month follow-up was partial: a significant improvement was observed on the Specific Phobia Questionnaire but not on the Medical Fears Survey or life interference measure. These findings provide preliminary support for VRET as a promising early-phase intervention for fear of needles, though further research is needed to optimise session dosage, confirm longer-term effectiveness, and assess generalizability.

5.1 Introduction

The general context for this study, including an overview of subclinical anxiety, exposure-based therapy, and VRET, is provided in Chapter 1. This introduction focuses on the case-specific literature relevant to fear of needles and the rationale for applying VRET to this population.

Fear of needles, also known as *needle phobia* or *trypanophobia*, is characterized by an intense fear of medical procedures involving needles or injections. It often manifests with physiological symptoms such as increased heart rate, a sudden drop in blood pressure leading to fainting, or feelings of panic when exposed to needles (McLenon & Rogers, 2019). While fear of needles is widely recognized, it remains underdiagnosed and undertreated in the adult population, leading many to avoid necessary medical procedures due to embarrassment or distress (McLenon & Rogers, 2019).

The documented prevalence of fear of needles is substantial, affecting approximately 20-30% of adults, with higher rates in younger adults and women (McLenon & Rogers, 2019). The prevalence is even higher among individuals with chronic illnesses, with rates varying widely from 0.2-80% in diabetes patients, 17–52% in cancer patients, and 25–47% in those with chronic kidney disease (Duncanson et al., 2021). The avoidance behaviors associated with fear of needles can have significant public health implications, particularly when they interfere with vaccination adherence, blood donation, and routine medical care, contributing to poorer health outcomes.

Despite the medical and public health burden, fear of needles is rarely formally diagnosed or treated (Alsbrooks & Hoerauf, 2022). While prior reviews have identified a number of studies on this topic (McLenon & Rogers, 2019), relatively few have focused specifically on general adult populations. Current first-line treatments include applied tension techniques to prevent fainting, and breathing exercises to manage panic responses (McLenon & Rogers, 2019). However, these methods do not address the underlying fear and avoidance behavior that perpetuate the phobia (Ayala et al., 2009). Another first-line intervention, exposure-based therapy, directly targets these underlying mechanisms. While applied tension can be a useful adjunct to prevent vasovagal syncope during exposure, there is little evidence that it enhances the efficacy of exposure therapy in reducing fear itself (Ayala et al., 2009).

5.1.1 Exposure-Based Therapy

Exposure therapy is the gold-standard treatment for anxiety-related disorders, including specific phobias (Norton & Price, 2007). It involves gradual, systematic exposure to the feared object or situation, helping individuals learn that their feared outcomes do not materialize, ultimately reducing their anxiety response (Odgers et al., 2022; Öst, 1989).

Exposure therapy is grounded in several theoretical models, primarily habituation and inhibitory learning. Traditionally, the habituation model posits that repeated exposure to a feared stimulus leads to a reduction in anxiety through a natural decline in the fear response over time (Benito & Walther, 2015). However,

more contemporary frameworks, such as the inhibitory learning model, suggest that exposure works by fostering new, non-threatening associations that inhibit the original fear memory rather than erasing it (Craske et al., 2012).

The exposure approach is commonly incorporated into cognitive-behavioral therapy and can be delivered in single- or multi-session formats. Recent research indicates no significant difference in efficacy between the two; however, a single-session exposure protocol is more time-efficient (Odgers et al., 2022). Despite its effectiveness, traditional exposure therapy can be costly and requires access to trained clinicians, which may not be feasible for many individuals seeking treatment (Conroy et al., 2020).

5.1.2 Virtual Reality-Delivered Exposure-Based Therapy

Virtual Reality Exposure-Based Therapy (VRET) is an innovative approach that offers an immersive and controlled environment for exposure-based treatment using virtual reality (VR) to deliver exposure. VRET has been found to be effective in treating various anxiety disorders, including post-traumatic stress disorder, social anxiety disorder, and specific phobias (Carl et al., 2019; Powers & Emmelkamp, 2008). By providing a virtual environment that simulates real-life scenarios, VRET eliminates many of the barriers associated with traditional exposure therapy, such as the need for in-person exposure to feared stimuli and access to specialized clinicians.

Despite the success of VRET in treating various anxiety-related disorders, its application to fear of needles remains under-explored. Many studies that utilize VR technology as a possible intervention for fear of needles investigate its usage as a distraction mechanism (e.g., Aydın and Özyazıcıoğlu, 2019; Chad et al., 2018; Tanja-Dijkstra et al., 2014), rather than a vehicle for exposure. Additionally, many studies on needle fear (e.g., Meindl et al., 2019; Özalp Gerçeker et al., 2020) focus on specific populations–such as children aged 5–12 and adults with Autism Spectrum Disorder–who are more prone to heightened fear responses and avoidance. In these cases, avoidance may be so significant that it necessitates more intensive interventions, such as physical restraint or sedation, particularly when individuals do not fully comprehend the importance of medical procedures.

To date, there is only one study (Jiang et al., 2020) that investigates the use of modern, non-smartphone-based head-mounted display VRET as an intervention for fear of needles in adults. This study was a pilot trial of 43 participants randomized into a single-session of VRET or a wait-list control group (Jiang et al., 2020). A single-session of VRET demonstrated the potential to alleviate fear of needle-related symptoms (Jiang et al., 2020). However, the study included solely diagnosed individuals, leaving a significant gap in the literature regarding the use of VRET for adults along a fear of needles spectrum. Another study (Lacey et al., 2022) employed smartphone-based VR delivered using 360° video and included participants with various phobias, including fear of needles. However, this approach differs in both technological immersion and the level of user interaction.

In addition, while existing studies often focus on symptom reduction, they frequently neglect the user experience of the intervention. This omission is especially critical, given that factors such as presence, plausibility, VR sickness, and

usability can influence both participant engagement and therapeutic outcomes. In VRET, the user's perception of the environment and comfort with the technology may be just as important as the therapeutic content itself. Furthermore, even the most effective intervention will fail if it is not deemed acceptable by those who need it; individuals are unlikely to engage with a treatment they find confusing, uncomfortable, or unpleasant. Therefore, examining user experience is essential to understanding not just whether VRET works, but for whom and under what conditions it is most effective.

5.1.3 Aims and Objectives

The current study aims to address the need for more research on VRET for fear of needles and to build on the findings of Jiang et al., 2020 by evaluating the preliminary effectiveness and acceptability of a VRET intervention for fear of needles in adults. Specifically, the study seeks to answer the following research questions pertaining to the preliminary effectiveness of the intervention and user experience:

1) Preliminary effectiveness of the intervention:

Does the intervention elicit anxiety as would be expected in a standard exposure-based protocol?

How effective is VRET in reducing fear of needles symptoms?

2) User experience and acceptability:

Do participants find the intervention acceptable?

How do participants perceive the VR experience (including VR sickness)?

Based on participant feedback, what aspects of the intervention could be improved to enhance user experience and therapeutic outcomes?

As an additional exploratory investigation, the study also seeks to answer whether individuals who underwent a single session VRET comprising of two exposures experienced reduced levels of anxiety when subsequently encountering images of needles and injections immediately after the intervention, when compared to individuals who did not experience the VRET.

By exploring these research questions, this study seeks to advance the understanding of VRET as a promising intervention for fear of needles and to explore its potential for improving scalable and accessible treatment options for affected individuals.

5.2 Methods

5.2.1 Participants

Two groups of participants were recruited: an experimental group and an online comparison group. Participants in the experimental group were recruited via Instagram advertisements and posters placed around the main campus of Imperial College London. The advertisements and posters directed participants to an online screening survey on Qualtrics. Inclusion criteria were being 18 years or older, English speaking, and reporting a fear of needles. The latter was defined as scoring a 1 or higher on the Specific Phobia Questionnaire (SPQ) blood-injection-

injury subscale and/or scoring a 1 or higher on the Medical Fears Survey (MFS) injections and blood subscale.

Exclusion criteria were reporting any condition precluding adherence to the measurement protocol (such as difficulty reading or writing), any uncorrected visual and/or auditory impairment affecting full participation in VR (use of corrective lenses or hearing aids was not a criterion for exclusion), current or past diagnosis of fear of needles, current or past treatment for fear of needles (excluding self-help), self-reported history of fainting from the sight of blood, presence or history of epilepsy, and history of severe motion sickness or dizziness. Individuals were also excluded if they self-reported currently taking medication that affected heart rate, such as benzodiazepines, as this could artificially decrease anxiety responses. Participants with a current or past diagnosis or treatment for fear of needles were excluded to ensure a treatment-naive sample and reduce potential confounding from prior clinical exposure or intervention. Those with a history of fainting at the sight of blood were excluded primarily for safety reasons, based on ethics committee guidance, and secondarily to avoid conflating fear of blood with fear of needles, given their potentially distinct psychological and physiological profiles.

Participants in the online comparison group were recruited via Prolific. They had the same inclusion and exclusion criteria as the experimental group, with the added criterion of self-reporting as UK-based and responding "yes" to "Would you be willing to participate in trialing a virtual reality intervention for fear of needles?". This inclusion criterion was established to enhance the comparability with the experimental group. They were also asked to respond to two attention-check questions and were only included if they answered correctly to both, ensuring they were reading and responding to the survey carefully. Due to resource and planning constraints, comparison group participants did not complete the one-month follow-up survey. As this was an exploratory aspect of the study, we acknowledge this as a limitation for between-group longitudinal comparisons. The inclusion of a comparison group was motivated by the desire to go beyond a single-arm design and examine whether post-intervention anxiety responses to needle images differed between those who received VRET and those who did not, providing a preliminary signal of specificity of effect. This is consistent with the limited efficacy testing dimension of early-phase feasibility evaluation (Bowen et al., 2009). The original study design intended for the comparison group to be recruited in person alongside the experimental group. However, in-person recruitment did not yield sufficient participants within the available timeframe, and the comparison group was therefore recruited online via Prolific to ensure an adequate sample size. Explicit randomization between conditions was not implemented for two reasons. First, the two recruitment modalities were structurally incompatible with a randomized allocation process, as the experimental group required in-person attendance at an Imperial College laboratory while the comparison group completed surveys entirely online. Second, given the exploratory and feasibility-focused nature of the study, the priority was to assess whether the intervention could be delivered acceptably and whether it produced a detectable anxiety response, rather than to establish causal efficacy through a fully controlled design. It is acknowledged that the difference in recruitment method

likely contributed to baseline differences between the groups. Baseline comparability was assessed using Wilcoxon rank-sum tests and is reported in Table 5.2; significant baseline differences in symptom severity and life interference were observed, which limits the interpretability of between-group comparisons and is acknowledged as a key limitation of the study design.

Previous meta-analyses of VRET for anxiety-related disorders reported effect sizes ranging from $d = 0.88$ to $d = 1.08$ (Carl et al., 2019; Powers & Emmelkamp, 2008). These estimates are drawn from meta-analyses spanning multiple anxiety disorders and a range of protocol designs, including multi-session interventions and both clinical and non-clinical populations. They are therefore not directly comparable to the present single-session pilot targeting subclinical fear of needles. However, in the absence of fear of needles-specific or single-session VRET effect size data at the time of study design, these meta-analytic estimates represented the best available benchmarks for an a priori power calculation. Their use is acknowledged as a limitation of the sample size estimation. With an alpha of 0.05 and a power of 0.95, a sample size of 37 participants in each group is required to detect a $d = 0.88$ effect size, and 25 participants in each group are required to detect a $d = 1.08$ effect size. Given the a priori power analysis, feasibility of recruitment, and the limited availability of condition-specific effect size data, we aimed to recruit 25 to 37 participants per group.

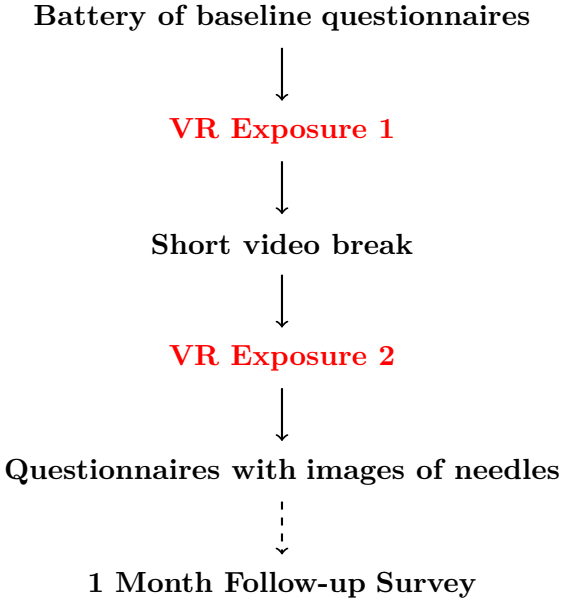
A total of 62 participants (32 in the experimental group and 30 in the comparison group) were recruited and provided informed consent. All participants in the experimental group who completed the in-lab session received £7 reimbursement as an Amazon voucher. If they also completed the one-month follow-up survey, they received an additional £3. All 32 participants in the experimental group completed the in-lab portion of the study. Due to a fire alarm during one participant's session, data from the onset of the alarm to session end was partially excluded and subsequently imputed to retain as much data as possible. 2 participants did not complete the follow-up survey. Participants in the comparison group were reimbursed £10/hour through Prolific. 75 potential participants responded to the Prolific advertisement and met the inclusion and exclusion criteria. Of these, 30 participants completed the comparison group surveys and correctly answered both attention check questions, constituting the final comparison group.

All study procedures were conducted in accordance with the ethical principles outlined in the World Medical Association's Declaration of Helsinki. Ethics approval for study measures and protocol was granted by the Research Governance and Integrity Team at Imperial College London (ref: 6577424).

5.2.2 Procedure

Participants in the experimental group who met the inclusion criteria and consented to take part in the study were invited to an in-lab session where they were given an online Qualtrics survey to collect baseline information on fear of needles symptoms using the SPQ and the MFS subscales and trait anxiety using the PROMIS anxiety. Participants were then given a brief information sheet about exposure therapy and read a short script providing the context to the VR scenario they would experience shortly. Before entering the VR environment, par-

Figure 5.1. Experimental Group Protocol



ticipants were asked to select the skin color of their VR avatar. This was done to enhance the experience of embodiment in the virtual environment. Participants then experienced two identical self-paced VR exposures and viewed a short neutral video between exposures to return to baseline. The general single-session VRET approach is consistent with prior protocols (e.g., Andersson et al. (2023), Inozu et al. (2021) and Jiang et al. (2020)). However, the single session was split into two identical exposures to reduce novelty-induced anxiety during the second exposure. The five-minute neutral video, which showed clips of animals from the documentary series *Baby Planet*, has been used in previous psychological studies to reset affective responses between tasks. Each exposure was self-paced, meaning participants were able to move through the VR scenario at their own pace and indicate to the researcher when they were ready to proceed through each stage. On average, each exposure lasted approximately ten minutes. This duration reflected the finite sequence of actions and events available in the VR software, which included the following in order: overhear other avatars discuss their recent injection experiences, entering the clinic room from the waiting room, experiencing a finger-prick blood test, an injection, a blood draw, and finally a longer (i.e., multi-vial) blood draw. During each exposure, anxiety was measured four times using the SUDS, administered verbally. The PANAS was administered three times: after the first exposure, after the break between sessions, and after the second exposure.

When participants were virtually pricked with a needle during the VR exposures, the sensory experience was replicated in reality by the experimenter poking the participant in the same location on the same arm with a blunt tool. This was done to further enhance embodiment during the VRET intervention.

Following the second VR exposure, participants completed several post-intervention measures. These included the SSQ, a set of custom questions assessing VR presence and plausibility adapted from Slater (2009), and the SUS. Participants also

responded to open-ended questions about the acceptability and usability of the VR experience (e.g., "How was your experience and the way you felt similar to your experience receiving a real injection? How was it different?" and "In your opinion, is there anything that could have been done differently to improve the software or create a better experience in any aspect?").

Immediately after completing these measures, participants viewed three photos of needles and injections, and were asked about their levels of anxiety (SUDS) immediately before and after. Positive and negative affect (PANAS) was also measured after viewing the photos. The PANAS administered after the second exposure also served as the pre-photo affect measure. These photos were selected for ability to elicit anxiety in a previous focus group of individuals with heightened fear of needles and injections.

One month later, an online follow-up survey was emailed to participants. They first responded to open-ended questions about their attitudes relating to needles. They then completed the SPQ and MFS subscales to assess fear of needles symptoms and associated life interference, as well as the SUDS for momentary anxiety. After viewing the same three needle images, they again completed the SUDS and PANAS to assess post-photo anxiety and affect. A schematic of the experimental group's protocol is shown in Figure 5.1.

Participants in the comparison group who met the inclusion criteria and gave consent were directed to an online Qualtrics survey. The survey collected information on fear of needles symptoms (MFS and SPQ), life interference (SPQ), baseline positive and negative affect (PANAS), and baseline anxiety (PROMIS anxiety). They were then asked to view the same needle and injection photos as the experimental group and completed the SUDS and PANAS immediately before and after. The comparison group did not receive the VRET intervention.

5.2.3 VRET Intervention

The VRET intervention was designed to function as a single-session exposure-based protocol consistent with established principles of exposure therapy for specific phobias (Norton & Price, 2007). Prior to entering the VR environment, participants received a brief information sheet explaining the rationale for exposure therapy and a standardized verbal script contextualizing the VR scenario they were about to experience. This psychoeducation was intentionally brief to avoid extensive cognitive preparation that could function as a safety behavior, consistent with inhibitory learning principles (Craske et al., 2014). The VR environment and its exposure sequence were developed by XRHealth's clinical team and were not designed by the research team. The sequence of needle-related procedures within the environment progressed from lower to higher levels of direct contact with feared stimuli: overhearing other avatars discuss their recent injection experiences, entering the clinic room from the waiting room, experiencing a finger-prick blood test, receiving an injection, undergoing a standard blood draw, and finally a longer multi-vial blood draw. This ordering is broadly consistent with a graduated exposure hierarchy, with higher-intensity procedures positioned at the end of the sequence. However, the specific rationale and design decisions underlying this hierarchy were made by XRHealth and are not fully documented

in the published literature. Participants completed all stages in order at their own self-determined pace, consistent with self-paced exposure protocols (Inozu et al., 2021). No safety behaviors were formally incorporated into the study protocol. Participants were not instructed to use relaxation techniques, breathing exercises, or applied tension during the exposure. A researcher was present throughout the session to manage the technical aspects of the VR system, administer the SUDS prompts verbally, and operate the blunt tactile tool to replicate needle sensations at the appropriate moments in the scenario. The researcher did not provide therapeutic coaching or in-session guidance beyond these technical functions, reflecting the self-guided nature of the protocol and its potential for scalable delivery. The single session was split into two identical exposures with a five-minute neutral video break between them. This design was adopted to allow assessment of within-session habituation across repeated exposures, and to examine whether anxiety levels in the second exposure differed from the first as a result of reduced novelty (Inozu et al., 2021).

5.2.4 Measures

Demographics. Participants self-reported age, sex, and whether their gender identity matched their sex registered at birth. Demographic data collection was intentionally kept minimal to reduce participant burden and survey length, which was a consideration given the additional time required for the in-lab VR session. Broader demographic variables such as ethnicity, socioeconomic status, and education level were not collected. The implications of this for generalizability are discussed in the limitations section.

Psychiatric Diagnoses. Participants self-reported any past or current psychiatric diagnoses.

Fear of Needles and Injections. Participants reported symptoms concerning fear of needles and injections using the blood-injection-injury subscale of the symptom severity Specific Phobia Questionnaire (SPQ) at baseline ($\alpha = 0.74$) and at one-month follow-up ($\alpha = 0.85$), as well as the injections and blood subscale of the Medical Fears Survey (MFS) (baseline: $\alpha = 0.83$, follow-up: $\alpha = 0.80$). The SPQ was also used to measure life interference at baseline ($\alpha = 0.76$) and at one-month follow-up ($\alpha = 0.76$). The SPQ subscale consists of two 14-item scales (one measuring symptom severity and one measuring life interference of these symptoms) on a 5-point Likert scale, ranging from 0 (no fear/no interference) to 4 (extreme fear/extreme interference) (Ovanessian et al., 2019). The MFS subscale consists of 4 items on a 4-point Likert scale, ranging from 0 (no fear or concern at all), 1 (mild fear), 2 (considerable fear), to 3 (intense fear) (Olatunji et al., 2012). Open-ended questions were also included to provide descriptive information about participants' attitudes toward needles and injections.

Clinical cutoff scores for the SPQ and MFS are not universally established. Receiver Operating Characteristic analyses have been used in prior research to identify sample-specific thresholds on the SPQ symptom severity subscale, with scores ≥ 20 often indicating higher symptom severity (Ovanessian et al., 2019). However, these thresholds are not validated as formal diagnostic cutoffs. No similar sensitivity or specificity indicators exist for the MFS subscale. Consequently,

scores in the current study were interpreted cautiously and used primarily for within-sample comparison rather than formal diagnosis.

Anxiety & Affect. Baseline trait anxiety was measured using Patient Reported Outcomes Measurement Information System - Anxiety (PROMIS anxiety), a 29-item questionnaire with a 5-point Likert scale ($\alpha = 0.96$) (Pilkonis et al., 2011). Response items ranged from 1 (never) to 5 (always). Momentary (or state) anxiety was measured using Subjective Units of Distress Scale (SUDS), which is one item with an 11-point Likert scale (responses ranging from 0 to 10) and was verbally administered during each VR exposure (Wolpe, 2018). To measure positive and negative affect, the short-form of the Positive and Negative Affect Schedule (PANAS-SF; Watson et al., 1988) was administered at baseline ($\alpha = 0.80$), after the first VR exposure ($\alpha = 0.93$), after the break between exposure sessions ($\alpha = 0.84$), and after the second VR exposure ($\alpha = 0.89$). It was also given in the follow-up survey ($\alpha = 0.94$). The PANAS comprised two scales (one for positive affect and one for negative affect), both on a 5-point Likert scale, from 1 (very slightly or not at all) to 5 (extremely). The PANAS-SF was administered in its state format, where participants rated how they felt "right now" rather than over the past week. While the PANAS-SF has not been formally validated for state measurement, it has been used in prior studies to assess momentary affective responses to brief interventions (e.g., Smith et al. (2021)). Importantly, the original PANAS has demonstrated strong psychometric properties for both trait and state affect measurement, providing a conceptual foundation for this adaptation (Watson et al., 1988). Measuring state affect across time points enabled us to examine the emotional impact of the intervention, including whether participants experienced emotional relief, regulation, or recovery following virtual exposure. Prior VRET studies have documented reductions in negative affect and increases in positive affect following virtual exposure sessions (e.g., Kan et al. (2025) and Zainal et al. (2021)). Reductions in negative affect following exposure therapy may indicate habituation or reduced fear generalization, while increases in positive affect may reflect perceived coping or mastery (Craske et al., 2014; Stewart et al., 2017). These dynamics help contextualize the immediate psychological impact of a brief, single-session exposure.

User Experience & Acceptability. VR presence and plausibility were measured by two questions modeled closely after Slater (2009). To measure plausibility, we asked participants to compare the virtual environment to receiving 1) a real injection and 2) an imagined injection. The responses are on a 5-point Likert scale, where 1 is much more anxious in VR and 5 is much more anxious in the real or imagined injection. Responses to each item were analyzed individually. VR sickness was measured using the Simulator Sickness Questionnaire (SSQ) at baseline ($\alpha = 0.81$) and post-intervention ($\alpha = 0.83$). The SSQ is on a 4-point Likert scale, ranging from 0 (not at all) to 3 (severe) (Kennedy et al., 1993). To assess usability, participants completed the System Usability Scale (SUS), which has a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree) and an alpha of 0.88 (Brooke, 1995). Scores range from 0 to 100 with a score of ≥ 68 being indicative of above-average user experience (Bangor et al., 2008). It is a validated questionnaire widely used to evaluate user experience with digital systems (J. R. Lewis, 2018). While the SUS does not provide a direct psychometric

assessment of acceptability, we included it as a pragmatic, quantifiable proxy for usability-related components of acceptability. This approach is consistent with recent digital health research (e.g., Bangor et al. (2008), Collins-Pisano et al. (2024) and Isaacs et al. (2023)) and is conceptually aligned with the Theoretical Framework of Acceptability (Sekhon et al., 2017), which identifies usability and burden as key constructs.

To capture a broader understanding of acceptability beyond usability, we supplemented the SUS with open-ended questions for descriptive analysis, addressing experiential, cognitive, and affective dimensions of the intervention. These included prompts such as: "How did you feel while you were taking part in the virtual reality experience?" and "How was your experience and the way you felt similar to your experience receiving a real injection? How was it different?" These items allowed us to assess subjective impressions of the intervention's realism, emotional impact, and overall acceptability from the user's perspective.

5.2.5 Equipment & Environment

The VR environment we used was developed by Amelia by XRHealth. The participants engaged in an environment depicting a medical clinic (Figure 5.2).

Participants began sessions by sitting in a clinic waiting room, where other patients can be heard discussing their recent injections and characterizing them as painful. A clinician then invited the participant into the clinic room. Upon entering, they saw vials and other blood-taking equipment as the clinician prepared for the appointment. The participant sat in the patient chair (i.e., they simultaneously sat in a chair in the real world to mirror their position in VR) and experienced a virtual finger-prick blood test, injection, blood draw, and a longer (i.e., multi-vial) blood draw (Figure 5.3). The software was run on a PICO G2 HMD VR headset.

The VR environment was controlled through Amelia by XRHealth's online platform. In this study, participants completed the actions in the given order (i.e., overhear other avatars discuss their recent injection experiences, enter the clinic room from the waiting room, finger-prick blood test, injection, blood draw, and longer blood draw) at their own pace. To limit VR sickness and heighten the sense of plausibility and immersiveness of the virtual environment, participants were asked to remain seated during the VR session.

5.2.6 Data Analysis

This study was preregistered (https://aspredicted.org/ykc7-62nr.pdf) with several deviations from the original preregistration. Specifically, the Distress Tolerance Scale and the Patient-Reported Outcomes Measurement Information System Anxiety & Perceived Stress measures were not included in the current analyses, as they were beyond the scope of the current research objectives but may be examined in future analyses. Additionally, physiological data collected during the study were not reported in this paper, but will be reported and analyzed in a subsequent paper. Sample size adjustments were also made, resulting in 32 participants per group instead of the initially planned 30 participants per group,

Figure 5.2. Screenshot of the VR Environment Depicting a Medical Clinic

Figure 5.3. Screenshot of the VR Environment Depicting a Finger-Prick Blood Test

to accommodate recruitment outcomes. Furthermore, the originally intended Bayesian analyses were replaced by frequentist analyses, as frequentist methods provided greater alignment with the exploratory nature of the data and facilitated interpretation of results within the existing research framework. Lastly, descriptive analyses of open-ended questions using Linguistic Inquiry and Word Count software were omitted in favor of descriptive reporting to streamline the presentation and discussion of results.

Statistical analyses were performed in R 4.4.0. Data were analyzed to explore preliminary effects of the intervention in evoking anxiety, preliminary effects on reducing symptoms, and user experience. To examine preliminary effects of the intervention in evoking anxiety and explore changes in positive and negative affect, Wilcoxon rank-sum tests and Friedman Rank Sum tests were used to compare pre- and post-intervention scores for negative affect, positive affect, and anxiety

levels. Paired t-tests were used to examine preliminary effects of the intervention in reducing symptoms of fear of needles. Effect size calculations were conducted to investigate magnitude of changes. To further evaluate the possible effects of a single session, Wilcoxon rank-sum tests were performed to compare participants' anxiety levels and related magnitudes of change after viewing photos of needles and injections. To examine user experience, descriptive data for participants' virtual sense of presence and plausibility, descriptive data for intervention acceptability, frequency of item endorsement on the SUS, and open-ended participant feedback for areas of intervention improvement were investigated. Exploratory analysis using Wilcoxon Signed Rank tests comparing the experimental and comparison groups examined if the VRET intervention elicited anxiety. To further explore the potential effects of a single session of VRET on fear of needles, participants' positive and negative affect were compared between groups after they had encountered images of needles and injections using Wilcoxon rank-sum tests.

2.15% of the experimental group's data and 0.91% of the comparison group's data were missing either at Random or Completely at Random. This was addressed using random forest run via the MissForest R package, which outperforms comparable data imputation methods (Stekhoven & Bühlmann, 2012). Statistical significance was defined at $p < .05$.

5.3 Results

A summary of participant characteristics for both groups is provided in Table 5.1. The experimental group comprised 25 females and 7 males aged 18–48 ($M = 25.31$, $Mdn = 21$, $SD = 8.60$), while the comparison group comprised 18 females, 11 males, and 1 participant who preferred not to say, aged 22-74 ($M = 36.90$, $Mdn = 37$, $SD = 11.80$). As noted in the limitations section, significant baseline differences in symptom severity and life interference were observed between the two groups (see Table 5.2).

Table 5.1. Participant Characteristics by Group

Characteristic	Experimental Group	Comparison Group
Demographics		
N	32	30
Age, *M* (*SD*)	25.31 (8.60)	36.90 (11.80)
Age, *Mdn*	21	37
Age range	18–48	22–74
Female, *n* (%)	25 (78.13)	18 (60.00)
Male, *n* (%)	7 (21.88)	11 (36.67)
Preferred not to say, *n* (%)	0 (0.00)	1 (3.33)
Gender matches sex at birth, *n* (%)	31 (96.88)	29 (96.67)
Prior VR experience, *n* (%)	13 (40.63)	–
Baseline Outcome Scores		
Symptom Severity (MFS), *M* (*SD*)	10.03 (3.23)	6.66 (2.65)
Symptom Severity (SPQ), *M* (*SD*)	41.06 (9.60)	30.07 (12.02)
Life Interference (SPQ), *M* (*SD*)	29.31 (11.22)	24.07 (10.76)

Note. Baseline outcome scores represent pre-imputation values. Significant baseline differences between groups were observed on all three outcome measures (all $p \leq .03$; see Table 5.2). Prior VR experience was not assessed in the comparison group.

The participants' baseline fear of needles symptoms, as measured by the SPQ and MFS subscales, as well as life interference due to fears are displayed in Table 5.2.

Table 5.2. Baseline Fear of Needles and Associated Life Interference

	Experimental Group			Comparison Group			Wilcoxon Rank-Sum Test	
	M	Mdn	SD	M	Mdn	SD	W	P
Symptom Severity (MFS)	10.03	10.00	3.23	6.66	6.0	2.65	767.50	<.001
Life Interference (SPQ)	29.31	27.00	11.22	24.07	20.00	10.76	638.50	0.03
Symptom Severity (SPQ)	41.06	43.00	9.60	30.07	27.50	12.02	740.00	<.001

Note. This table represents data pre-imputation.

A table of correlations between the main study variables are displayed in Table 5.3.

Table 5.3. Correlation Table of Main Study Variables

Variable 1	Variable 2	Correlation	FDR-Corrected p-value
baseline life interference	age	0.03	0.90
baseline severity (SPQ)	age	-0.05	0.83
baseline severity (MFS)	age	-0.26	0.13
baseline pos affect	age	0.29	0.08
baseline neg affect	age	-0.02	0.93
PROMIS anxiety	age	-0.03	0.90
anxiety in exposure 1	age	0.13	0.71
anxiety in exposure 2	age	0.12	0.73
life interference after VRET	age	0.30	0.21
severity after VRET (SPQ)	age	0.28	0.23
severity after VRET (MFS)	age	-0.04	0.90
baseline severity (SPQ)	baseline life interference	0.80	$< .001$
baseline severity (MFS)	baseline life interference	0.73	$< .001$
baseline pos affect	baseline life interference	0.10	0.68
baseline neg affect	baseline life interference	0.24	0.17
PROMIS anxiety	baseline life interference	0.28	0.10
anxiety in exposure 1	baseline life interference	0.19	0.46
anxiety in exposure 2	baseline life interference	0.32	0.17
life interference after VRET	baseline life interference	0.56	0.01
severity after VRET (SPQ)	baseline life interference	0.47	0.03
severity after VRET (MFS)	baseline life interference	0.44	0.05
baseline severity (MFS)	baseline severity (SPQ)	0.80	$< .001$
baseline pos affect	baseline severity (SPQ)	0.04	0.90
baseline neg affect	baseline severity (SPQ)	0.18	0.31
PROMIS anxiety	baseline severity (SPQ)	0.26	0.12
anxiety in exposure 1	baseline severity (SPQ)	0.23	0.35
anxiety in exposure 2	baseline severity (SPQ)	0.30	0.21
life interference after VRET	baseline severity (SPQ)	0.41	0.08
severity after VRET (SPQ)	baseline severity (SPQ)	0.48	0.03
severity after VRET (MFS)	baseline severity (SPQ)	0.37	0.12

5.3.1 Preliminary Effects of the Intervention

Figure 5.4 shows a graph of average anxiety levels over both VR exposure sessions. Anxiety increased from baseline as participants interacted with the medical clinic VR environment and received virtual injections, and remained elevated as they received blood tests. Highest levels of anxiety were achieved when interacting most with the virtual needles. Participants reported higher average levels of anxiety during the first compared to the second exposure.

Figure 5.4. Anxiety During Both VR Exposures

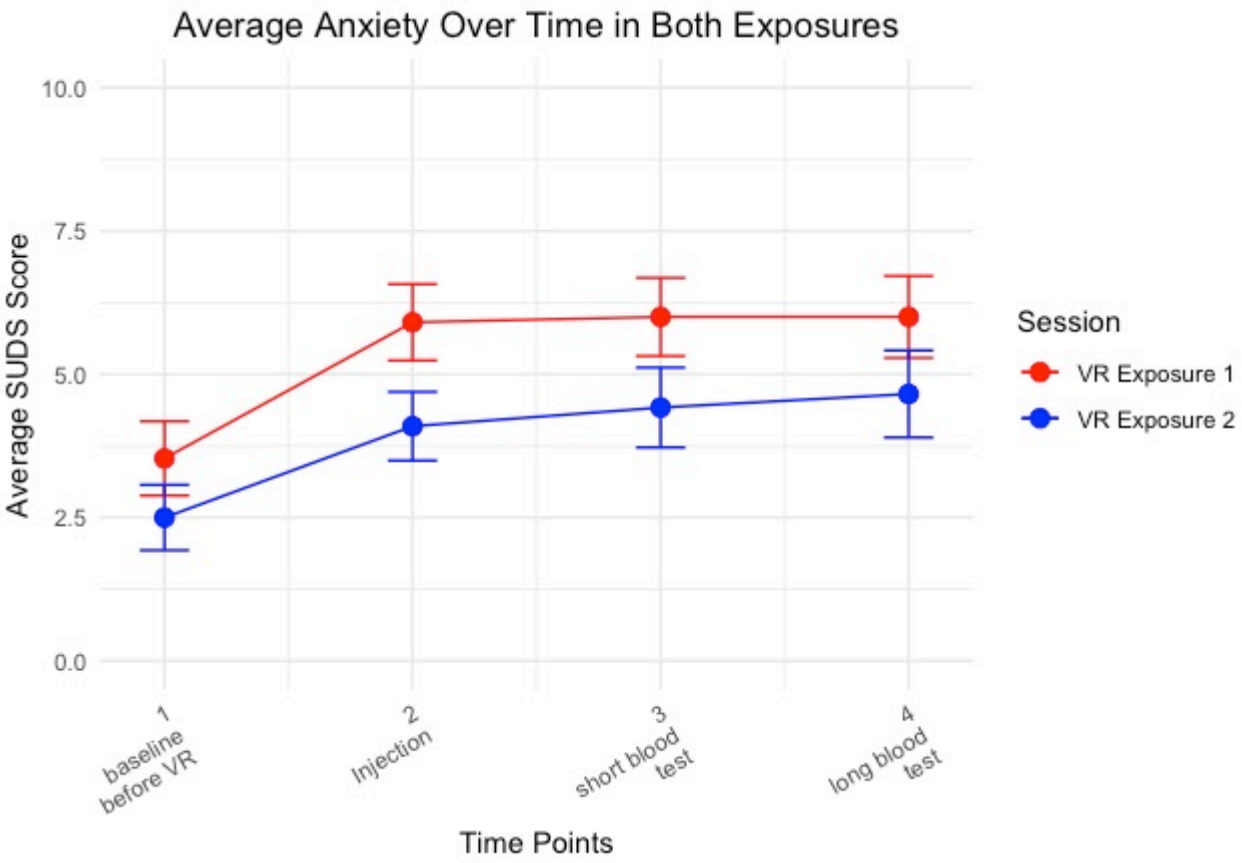
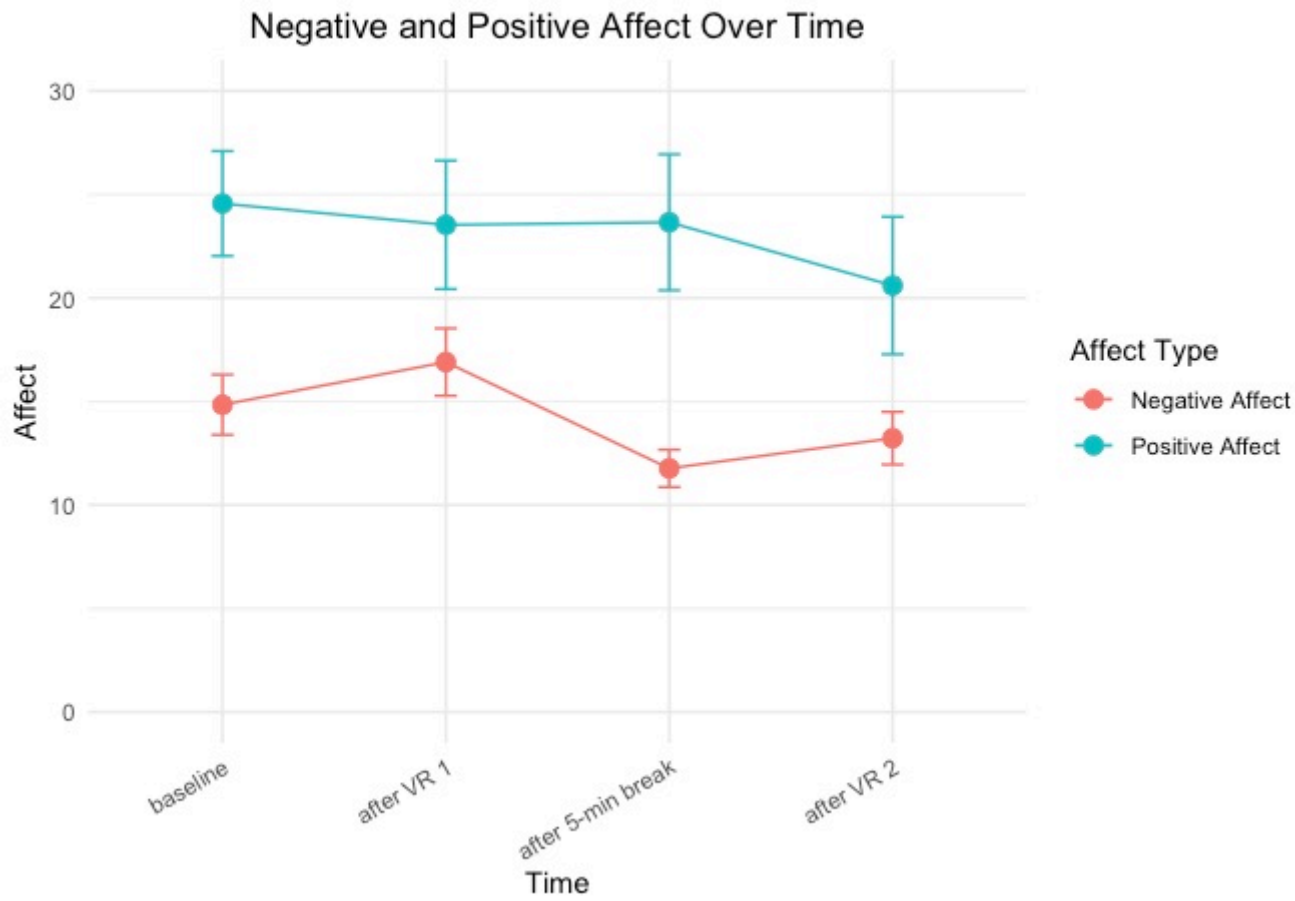


Figure 5.5 shows average negative and positive affect over time, with positive affect remaining relatively level and then dropping slightly after the 2nd VR exposure. Negative affect increased slightly from baseline to after the 1st VR exposure and decreased as expected during the break, before increasing slightly again during the 2nd VR exposure.

Figure 5.5. Average Positive and Negative Affect Across Both VR Exposures



To examine if the VRET intervention elicited anxiety and how it affected positive and negative affect in the experimental group, a series of Wilcoxon Signed Rank tests were conducted (Table 5.4). A statistically significant reduction in anxiety was demonstrated in the experimental group from baseline to post-intervention ($p = .02$). A statistically significant change in positive affect was also found ($p < 0.001$). As expected, no significant change was seen in negative or positive affect in the comparison group, who did not receive the intervention.

To investigate changes in affect and anxiety during the intervention, in accordance with the assumptions of normality, Friedman tests were conducted for the repeated measures (Table 5.5). Statistically significant change ($p < 0.001$) was seen for positive affect, negative affect, and anxiety during the VRET.

To examine the preliminary effects of a single session of VRET in reducing fear of needles symptoms, a paired t-test was conducted on symptom severity score at baseline pre-intervention and at one-month follow-up using the MFS. The results were not statistically significant ($t(31) = 1.39$, $p = .18$, 95% CI [-0.30, 1.57]). A paired t-test was also conducted using SPQ as a measure of symptom severity. These results were significant ($t(31) = 2.24$, $p = .03$, 95% CI [0.33, 7.21]), indicating a reduction in symptom severity (i.e., post-intervention

Table 5.4. Wilcoxon Signed Rank Test Results at Baseline Versus Post-Intervention

	V	p-value	Median Difference
Experimental Group			
Anxiety (SUDS)	329.00	0.02	-1.00
Negative affect (PANAS)	171.50	0.48	0.04
Positive affect (PANAS)	400.00	$< .001$	-6.30
Comparison Group			
Negative affect (PANAS)	77.50	0.19	0.00
Positive affect (PANAS)	214.00	0.07	-0.50

Table 5.5. Friedman Test Results for Anxiety and Affect During Intervention

Measure	Chi-Squared (χ^2)	df	p-value
Neg affect (PANAS)	40.07	3	$< .001$
Pos affect (PANAS)	34.67	3	$< .001$
Anxiety (SUDS) during exposure 1	38.51	3	$< .001$
Anxiety (SUDS) during exposure 2	34.94	3	$< .001$

SPQ scores were lower than pre-intervention scores), suggesting the intervention might have influenced participant fear of needles. A paired t-test examining life interference at baseline and at one-month follow-up was not significant ($t(31) = -0.15$, $p = .88$, 95% CI [-3.21, 2.78]).

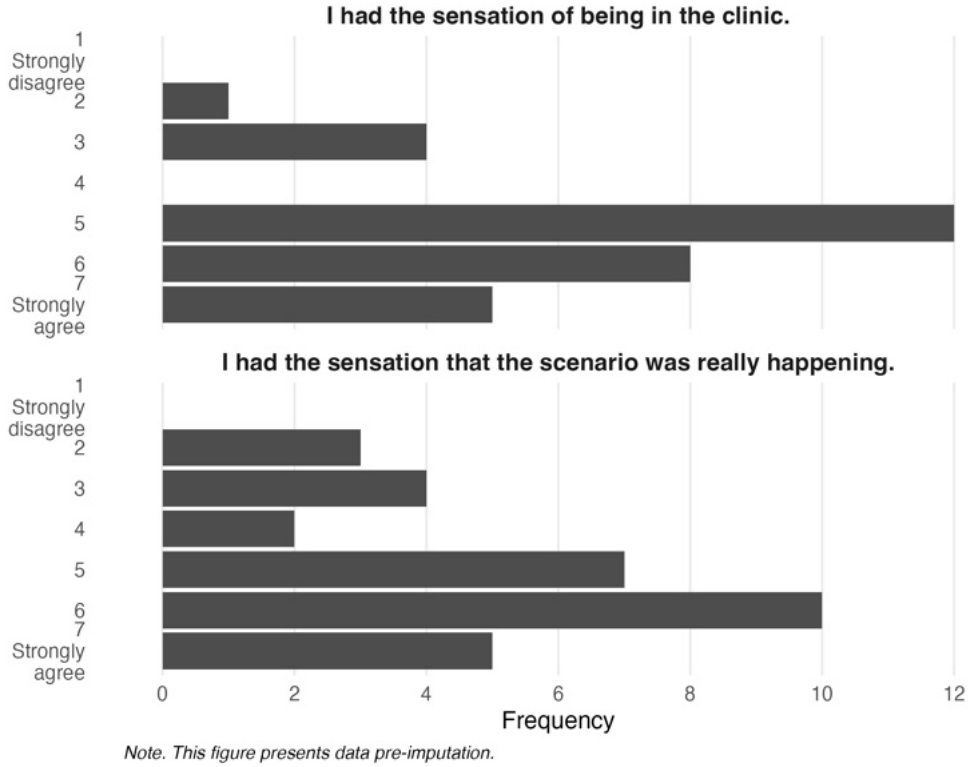
To further evaluate the possible effects of this single session of VRET on fear of needles, participants' anxiety levels after encountering images of needles and injections were compared between groups. Before viewing the photos at baseline, anxiety levels did not differ between the groups ($W = 565.00$, $p = .23$, $r = 0.15$). However, after viewing the same photos of needles and injections, the experimental group reported significantly lower anxiety levels compared to the comparison group ($W = 695.00$, $p = .002$, $r = 0.39$). Furthermore, the reduction in anxiety from pre- to post-exposure was significantly greater in the experimental group, indicating a moderate effect of the intervention ($W = 684.00$, $p = .004$, $r = 0.37$).

To independently assess the magnitude of change in symptom severity, life interference, and affect from baseline to one-month follow-up, a series of standalone effect size calculations were conducted. A small effect size indicated a difference in symptom severity between baseline and one-month follow-up contamination scores of $g = 0.23$ for the MFS and $g = 0.35$ for the SPQ. Effect size was negligible ($g = 0.009$) for life interference. For negative affect, a small negative effect size ($g = -0.35$) was found, while a large positive effect size ($g = 0.87$) was found for positive affect. This suggests a small decrease in negative affect and a large increase in positive affect.

5.3.2 User Experience

To explore how participants in the experimental group perceived the virtual environment, VR presence (i.e., feeling physically present and engaged in the VR environment) and plausibility were investigated.

Figure 5.6. Frequencies of Endorsement for Presence in the Virtual Environment

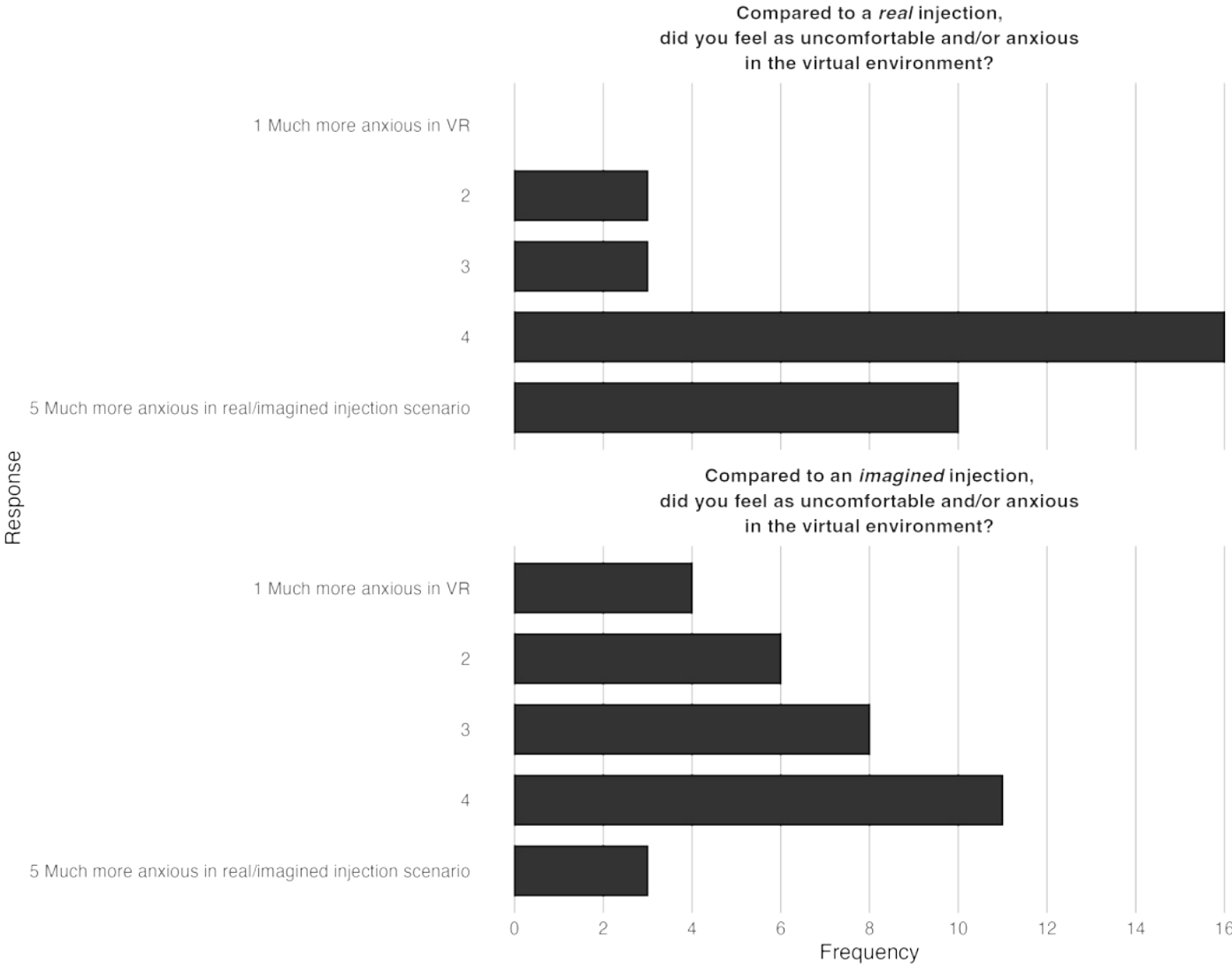


Note. This figure presents data pre-imputation.

Figure 5.6 explores participant responses for questions related to virtual presence. Responses indicate that the majority of participants who experienced the VRET intervention believed it captured the sensation of being in a medical clinic ($M = 5.22$, $SD = 1.27$) and that the scenario was really happening ($M = 5.00$, $SD = 1.54$).

Figure 5.7 displays the findings related to plausibility in the virtual environment. There was a varied response from participants; when compared to a real ($M = 4.03$, $SD = 0.88$) and an imagined scenario ($M = 3.09$, $SD = 1.18$), some found the virtual environment anxiety-provoking, while others did not.

Figure 5.7. Frequencies of Endorsement for Plausibility in the Virtual Environment



Note. This figure presents data pre-imputation.

Participants reported high levels of usability for the VRET intervention, with average scores of 73.36 ($Mdn = 75.00$, $SD = 17.29$) on the SUS, where a score of 68 is generally considered average and acceptable (Bangor et al., 2008; Hyzy et al., 2022). Many participants reported that they would like to use the VR system frequently ($M = 3.19$, $SD = 1.07$). They thought it was easy to use ($M = 4.00$, $SD = 1.12$), would not need the support of a technical person to be able to use it (reverse coded: $M = 1.97$, $SD = 0.85$), believed that most people would learn to use it very quickly ($M = 3.91$, $SD = 0.80$), and felt very confident using it ($M = 3.75$, $SD = 1.03$). Additionally, they did not find the system unnecessarily complex (reverse coded: $M = 1.59$, $SD = 0.96$).

In the open-ended questions, a participant described using the intervention as "...a really good idea and helps rehearse the scenario beforehand so it feels a lot

less anxiety inducing. It felt quite real." Another participant wrote, "I actually think that if I did this periodically over a few months and especially right before an injection, it could help my phobia. I think my fear is heightened because I don't often have injections, so my anxiety is higher when I have them because I am not used to them... This experience could help me get used to the process and seeing needles, which would hopefully make me calmer in that situation in real life. If there are needles on tv/in films I always look away but this has made me think my phobia could improve if I expose myself to them more, as they will become more normal." Complete participant feedback is listed in Table B.2 in the Appendix.

7 participants reported VR sickness at the end of the intervention. Table 5.6 examines VR sickness scores as measured by the SSQ at baseline and after the intervention. Disorientation was the highest reported symptom. Total VR sickness was substantially higher after the VRET intervention ($M = 101.23$, $Mdn = 93.50$) than at baseline before any VR engagement ($M = 19.95$, $Mdn = 11.22$). Total score for VR sickness ranged from 0 to 71.06 at baseline and 78.54 to 175.78 at the end of the intervention.

Table 5.6. Simulator Sickness Questionnaire Scores At Baseline and End of Intervention

	Nausea	**Oculomotor**	**Disorientation**	**Total Score**
	M, Mdn(SD)	M, Mdn(SD)	M, Mdn(SD)	M, Mdn(SD)
Baseline	14.46, 9.54 (14.12)	18.95, 11.37 (20.57)	19.76, 0.00 (33.48)	19.95, 11.22 (23.02)
End of Intervention	83.09, 76.32 (15.02)	72.77, 68.22 (18.20)	123.93, 111.36 (35.83)	101.23, 93.50 (21.54)

Participants suggested several areas of improvement to the VRET that might increase their feeling of engagement and immersion in the experience, such as the graphical representation of people in the environment. Some highlighted wanting more pressure or a pinch on their arm as their avatar received the injection in the VR environment to simulate the pain of receiving an injection. Participants also mentioned adding "sounds that you'd normally hear in a hospital [other than] conversations between people" and "more happening around me as it would be in a real clinic." Table B.2 in the Appendix includes a full list of participant feedback.

5.4 Discussion

This study aimed to build on previous literature to evaluate the preliminary effectiveness and acceptability of VRET for fear of needles in adults. Previous research on this topic has concentrated on specific subsets of various populations rather than adults more generally (e.g., Meindl et al., 2019; Özalp Gerçeker et al., 2020). Our study extends prior VRET work by specifically targeting fear of needles in adults with a range of severity of symptoms and examines user experience and acceptability as a central aim.

5.4.1 Preliminary Effects of the Intervention

The results suggest that VRET can effectively elicit anxiety during exposure while also being highly acceptable to participants. As expected, participants reported high levels of anxiety during virtual exposure to needle-related stimuli, supporting the validity of VRET as an exposure tool. The first VR exposure elicited higher average levels of anxiety compared to the second exposure, likely due to anticipatory anxiety and the novelty of the experience in the beginning. In the second VR exposure, participants demonstrated some habituation and were more familiar both with the environment and the protocol.

In addition to reductions in anxiety, we observed modest increases in positive affect and decreases in negative affect following the VR exposures. Although these changes could partially reflect participants' relief that the exposures had ended, such shifts may also serve as markers of emotional recovery and regulatory processing. Theoretical models of exposure therapy informed by inhibitory learning provide a conceptual framework for understanding this: effective emotion regulation and positive affect following exposure may enhance consolidation of new safety memories and reduce fear return, whereas poor affective recovery may undermine long-term outcomes (Craske et al., 2014; Zbozinek & Craske, 2017). These findings are also consistent with previous research reporting similar affective patterns following virtual exposure (Kan et al., 2025; Zainal et al., 2021). Thus, tracking positive and negative affect offers insight into participants' emotional coping and immediate intervention impact.

However, the findings regarding symptom reduction were more nuanced. While fear severity scores decreased significantly from baseline to post-intervention according to the SPQ, no significant change was found using the MFS over this period of time. This discrepancy suggests that different measures of fear might capture distinct aspects of the phobic response, highlighting the need for further research into the most appropriate outcome measures for VRET interventions.

While the immediate reductions in fear-related symptoms were promising, the findings indicate that a single session may not be sufficient for long-term change. Instead, repeated exposure may be required to ensure lasting effects. One explanation for this is that a single session might create only a transient decrease in anxiety, whereas more extensive treatment protocols may be required to achieve lasting change. While a single session of exposure therapy can temporarily reduce fear, its effects may be short-lived because deep-seated fear responses often necessitate repeated exposure for lasting change. The mixed results indicate that a single session might not provide sufficient reinforcement to counteract these ingrained responses, underscoring the significance of multiple sessions to strengthen and solidify the benefits over time. However, further research is needed to determine the optimal number of sessions required to fully eliminate fear of needles.

Nevertheless, the current results provide compelling evidence that even a single session of VRET can effectively reduce anxiety related to needle phobia. The significant reduction in anxiety and increase in positive affect observed in the experimental group following the intervention suggests that VRET is a promising tool for addressing fear responses in subclinical populations. Notably, the comparison group, which did not receive the intervention, showed no signific-

ant changes in affect or anxiety, reinforcing the specificity of the VRET effect. Furthermore, the between-group analysis revealed that the experimental group experienced significantly lower anxiety after viewing needle-related images compared to the comparison group, despite no initial difference at baseline. This post-intervention contrast, alongside the greater reduction in anxiety within the experimental group, underscores the potential of VRET to buffer individuals against anxiety responses triggered by phobic stimuli. Taken together, these findings support the preliminary effectiveness of brief, targeted VRET interventions in modulating both emotional reactivity and affective states, particularly in the context of needle-related fears.

5.4.2 User Experience

A pivotal aim of this study was assessing the user experience and acceptability of VRET for adults with fear of needles. The results indicate that participants found the VR environment to be immersive and engaging, with participants reporting a moderate-to-strong sense of physical presence (feeling present in the environment: $M = 5.22$, $SD = 1.27$; feeling the scenario was really happening: $M = 5.00$, $SD = 1.54$). Plausibility ratings were moderate on average, with participants rating the scenario as more similar to a real than an imagined scenario ($M = 4.03$, $SD = 0.88$ and $M = 3.09$, $SD = 1.18$, respectively), suggesting the environment was sufficiently realistic to elicit meaningful emotional and physiological responses. This supports prior findings that VRET can effectively simulate real-world anxiety-inducing situations while maintaining a controlled and safe environment for participants (e.g., Carl et al., 2019; Jiang et al., 2020). Additionally, participants reported above-average usability on the SUS ($M = 73.36$, $Mdn = 75.00$, $SD = 17.29$; above-average threshold = 68). Item-level scores indicated that participants found the system easy to use ($M = 4.00$, $SD = 1.12$), felt confident using it ($M = 3.75$, $SD = 1.03$), and did not feel they needed the support of a technical person ($M = 1.97$, $SD = 0.85$, reverse coded).

Our findings suggest that the VR intervention was generally well received by participants in terms of both usability and broader experiential acceptability. Although the SUS does not directly assess acceptability, its use as a proxy for usability-related acceptability is consistent with digital health literature and the Theoretical Framework of Acceptability (Sekhon et al., 2017). Importantly, our interpretation of acceptability extended beyond SUS scores alone. Open-ended feedback captured participants' affective and cognitive responses, such as feelings of emotional engagement and willingness to use the intervention again. These qualitative data provided valuable context for understanding the overall acceptability of the intervention as a user-centered therapeutic tool.

Beyond usability and acceptability, we also examined participants' physical comfort and any adverse reactions associated with the VR experience. In interpreting the VR sickness findings, it is important to consider the potential overlap between symptoms captured by the SSQ and those that may arise from fear of needles. Physiological responses to fear, such as dizziness, nausea, and lightheadedness, can resemble symptoms typically associated with VR sickness. As such, elevated SSQ scores in this context may reflect, in part, participants' needle-

related distress rather than purely VR-induced discomfort. While this possibility does not undermine the utility of the SSQ, it does suggest that scores should be interpreted cautiously, particularly in phobia contexts where symptom overlap is likely. Future studies might benefit from collecting additional physiological or subjective data to help disambiguate the source of these symptoms.

The usability and acceptability of VRET underscores its feasibility as an alternative to traditional exposure therapy, particularly for individuals with difficulty accessing in-person treatment. This is in line with previous literature (Garcia-Palacios et al., 2007), which found a significantly lower rate of refusal for VRET compared to in vivo exposure. Open-ended feedback further emphasized the intervention's potential for reducing fear over time, with several participants suggesting that they believed repeated exposure to the virtual scenarios could help normalize needle-related experiences. Seven participants reported VR sickness at the end of the intervention (see Section 5.3.2), and two participants specifically mentioned motion sickness or nausea in their open-ended feedback, suggesting that improvements in VR technology and session structuring may enhance user comfort.

5.4.3 Limitations

This study has several limitations that affect its generalizability. First, the small sample size requires replication with a larger, more diverse sample. Second, demographic data collection was limited to age, sex, and gender identity. Broader demographic variables such as ethnicity, socioeconomic status, and education level were not collected, which limits the ability to assess whether the findings generalize across these dimensions. Given that fear of needles prevalence and treatment engagement may vary across demographic groups (McLenon & Rogers, 2019), future studies should collect and report a fuller range of demographic variables to support assessment of generalizability and potential moderators of treatment response. Third, the comparison group was recruited via Prolific, rather than using a control group that was randomized and recruited in the same manner as the experimental group. This difference introduces potential limitations in comparability. Nevertheless, individuals in the comparison group were asked if they would be willing to participate in a VR-delivered intervention targeting fear of needles. Those who declined were excluded from the group, enhancing comparability. Additionally, clinical cutoff scores for the SPQ and MFS are not formally established, and both instruments are typically interpreted using sample-specific thresholds. However, both the SPQ and MFS are validated, psychometrically sound instruments that are widely used in clinical and experimental research on specific phobias, including fear of needles. In the present study, scores were interpreted descriptively and used primarily to assess relative change and within-sample comparisons, rather than to make diagnostic determinations. The sample was also insufficiently powered to examine sex as a moderator of treatment response. Future research with larger samples should investigate whether sex is associated with differential outcomes following VRET for subclinical fear of needles.

5.4.4 Strengths

Despite limitations, this study offers several strengths. First, it addresses a critical gap in the literature by specifically examining VRET for fear of needles, rather than general blood-injection-injury phobia. Second, by focusing on a community sample of adults rather than narrower adult or pediatric populations, the study offers broader insights into needle fear across a diverse age range. Third, the study's central aim of examining user experience and acceptability alongside preliminary effectiveness provides valuable insights into the subjective experience of VRET, offering guidance for refining future VR-based interventions.

5.4.5 Implications for Research, Policy, and Practice

These findings carry implications for both future research and clinical practice. From a research perspective, future studies should prioritise randomised designs with in-person control groups to strengthen causal inference, and investigate the effects of multi-session VRET protocols, which remain largely unexplored for fear of needles and have strong potential for more durable outcomes. From a practice perspective, our results suggest that VRET has the potential to improve treatment accessibility for individuals with fear of needles and injections, with significant implications for public health. Given the importance of medical procedures involving needles, from vaccinations to blood tests, interventions that help individuals manage their fears are highly valuable. If validated in future larger-scale studies, VRET could serve as a scalable and accessible treatment for individuals who fear needles, ultimately improving medical adherence and health outcomes.

5.4.6 Conclusion

This study contributes to the growing body of research on VRET as a potential intervention for fear of needles in adults. The findings suggest that VRET can effectively elicit anxiety during exposure, while simultaneously being highly acceptable to participants. The following chapter extends the investigation of both case studies by examining the physiological signatures of anxiety during VRET exposure, exploring whether wearable sensor data and machine learning can be used to detect and differentiate anxiety states across the two subclinical presentations.

6 Wearable Detection of Divergent Anxiety Types: Comparing Physiological Signatures and Shared Arousal Patterns Using Machine Learning

ABSTRACT

Background: Contamination OCD anxiety and needle anxiety are distinct but functionally impairing anxiety subtypes. They differ in their autonomic signatures, with contamination OCD associated with sympathetic hyperactivation and needle anxiety associated with vasovagal responses. Despite these differences, both respond to exposure-based therapy and share experiential features that may give rise to common physiological patterns. **Objectives:** This study examined how physiological markers collected from a wearable device differ across contamination OCD and needle anxieties, and whether shared psychophysiological features can nonetheless be identified. It also assessed whether anxiety states and severity levels can be accurately detected in both groups. **Methods:** 48 participants (16 with contamination OCD anxiety and 32 with needle anxiety) were exposed to virtual reality scenarios designed to elicit anxiety. Heart rate HR, electrodermal activity (EDA), and skin temperature were collected using an Empatica E4 wearable. K-Nearest Neighbors (KNN), Support Vector Machine (SVM), Random Forest, and Decision Tree ML models were trained to classify anxious versus baseline states (Experiment 1) and symptom severity levels (Experiment 2), using 10-fold cross-validation. **Results:** Skin temperature was the most accurate single marker across both anxiety types, with classification accuracy improving when combined with EDA. KNN consistently outperformed other ML models, reaching up to 99.3% accuracy and 1.0 F1 score. While autonomic patterns diverged across symptom types, overlapping physiological features, particularly skin temperature and EDA, were observed in both. **Conclusions:** Physiological data from wearables can effectively detect anxiety and differentiate symptom severity across symptomatically and physiologically distinct presentations. These results suggest that specific physiological markers, especially skin temperature and EDA, may reflect shared arousal processes relevant to anxiety across diagnostic boundaries. The findings support the development of scalable, passive tools for early detection and monitoring of anxiety using wearable technologies.

6.1 Introduction

Psychophysiological measurement has become a central focus in anxiety research, offering objective insight into how autonomic responses reflect emotional states. With the growing availability of wearable technologies, there is increasing interest in whether physiological signals such as HR, EDA, and skin temperature can detect anxiety and inform transdiagnostic models of psychopathology. By examining psychophysiological responses across two distinct anxiety presentations with differing autonomic profiles, this study addresses two key gaps: the limited understanding of how physiological signatures vary across underrepresented anxiety types, and the broader question of whether common arousal patterns can be detected despite these differences.

Anxiety disorders are among the most prevalent mental health conditions globally, manifesting in diverse forms that can differ dramatically in expression, yet share underlying mechanisms (Javaid et al., 2023). As an example of this, contamination Obsessive-Compulsive Disorder (OCD) symptoms and needle anxiety represent distinct anxiety profiles with divergent autonomic signatures that can both be disruptive to day-to-day life and clinically relevant. There are thus good reasons to compare their psychophysiological signatures.

Contamination OCD anxiety is often a component of OCD, an anxiety-disorder characterized by intrusive thoughts, images, or urges, which are distressing and often result in repetitive physical or mental acts that the individual feels driven to perform (such as repeatedly washing hands) to temporarily alleviate the distress (Rasmussen & Eisen, 1992). OCD is widely recognized as a highly debilitating condition associated with significant income loss, reduced quality of life (Veale & Roberts, 2014), and considerable economic burden (Kochar et al., 2023). Its lifetime prevalence has been documented to be around 2.3%, according to the National Comorbidity Survey Replication, although this figure is likely underestimated due to stigma-related underreporting of symptoms (Brady et al., 2010; Kessler et al., 2012). Prevalence of subclinical OCD is likely higher. Among the various symptom dimensions of OCD, contamination and washing concerns are most prevalent, affecting up to 50% of individuals with OCD (Rasmussen & Eisen, 1992).

Needle-related anxiety (also called trypanophobia, needle phobia, or fear of needles) is described by an intense fear of medical procedures involving needles or injections. This fear often triggers physical reactions such as an elevated heartbeat, sudden drop in blood pressure that may cause fainting, or feelings of panic when encountering needles (McLenon & Rogers, 2019). This vasovagal reaction is not unique to needle anxiety; it has been reported in other types of fear/anxiety, such as hemophobia, panic disorder, and agoraphobia (Richter et al., 2021; Viar et al., 2010). It can manifest in times of extreme emotional distress and has been hypothesized as a mechanism to protect the heart in times of stress and possibly a vestige of an evolutionary selected trait (Alboni & Alboni, 2014, 2017).

The prevalence of needle phobia is significant, affecting roughly 20–30% of adults, with higher rates observed among younger adults and women, though this figure is likely an underestimate due to stigma-related underreporting of

symptoms (McLenon & Rogers, 2019). This fear is even more common among individuals with chronic conditions such as cancer, diabetes, and kidney disease. Reported prevalence varies widely, ranging from 0.2% to 80% in diabetes patients, 17% to 52% in cancer patients, and 25% to 47% in those with chronic kidney disease (Duncanson et al., 2021). The avoidance behaviors linked to needle fear can have serious public health consequences, particularly when associated with reduced vaccination rates, lower blood donation participation, and reluctance to seek necessary medical care, ultimately contributing to poorer health outcomes. Despite being a well-documented condition, needle anxiety is rarely formally diagnosed or treated, especially among adults, causing many to avoid essential medical procedures due to distress or embarrassment (Bienvenu & Eaton, 1998; McLenon & Rogers, 2019).

There are several compelling reasons to compare contamination OCD and needle anxiety. First, they represent informative case studies because they differ in autonomic profiles but share experiential features, such as anticipatory threat processing and avoidance behavior. Contamination OCD is associated with sympathetic hyperactivation, while needle anxiety involves a vasovagal response characterized by parasympathetic dominance. Despite these physiological differences, both involve anticipatory threat processing, avoidance behavior, and subjective experiences of fear. These similarities suggest the possibility of overlapping mechanisms of anxious arousal (Craske et al., 2014). While their physiological profiles are expected to diverge, their shared phenomenology raises the question of whether different autonomic routes may nonetheless produce similar patterns of felt anxiety. Comparing these two anxiety types reveals both distinct physiological signatures and potential shared patterns.

Second, although contamination OCD anxiety and needle anxiety differ in underlying autonomic pathways, they might converge in physiological anxiety expression. Skin temperature and EDA, for instance, reflect autonomic shifts that can occur in either direction, including both arousal and withdrawal. Skin temperature can decrease due to sympathetic vasoconstriction or parasympathetic withdrawal, while EDA, though largely linked to sympathetic activity, can also vary in parasympathetic-dominant contexts following anticipatory arousal. These markers may therefore not map neatly onto discrete anxiety subtypes, but instead capture broader disruptions in autonomic regulation. Studying these cases together thus helps capture generalizable arousal across diverse anxiety presentations.

Third, avoidance and threat anticipation are reflected in responses to similar treatments for both symptomatologies, despite differing autonomic signatures. The established gold-standard treatment for OCD is CBT incorporating Exposure and Response Prevention ('Clinical Guideline 31', 2005), which is regarded as an essential component. In exposure-based therapy, an individual systematically faces the feared stimuli within a safe context to facilitate anxiety habituation and/or belief disconfirmation (Odgers et al., 2022; Öst, 1989). Similar to contamination OCD anxiety, exposure-based therapy is the gold-standard treatment for specific phobias, of which needle-related anxiety is one (Norton & Price, 2007). Although needle anxiety involves a vasovagal response, where HR and blood pressure decrease, other anxiety disorders such as OCD typically involve increases in

these measures. Despite these differences, both conditions respond to exposure-based treatments that reduce fear through extinction learning. This indicates that, despite separate autonomic profiles, both conditions engage a shared underlying mechanism of inhibitory learning and habituation (Craske et al., 2012, 2014). The contrast between their distinct autonomic pathways and their shared response to exposure-based treatment raises a central question: how do physiological signatures differ across anxiety types, and are there convergent markers that reflect shared mechanisms of arousal? This distinction is especially important for transdiagnostic models, which aim not to erase heterogeneity but to identify signal patterns that recur across different symptom profiles. Rather than assuming a single physiological expression of anxiety, this study explores both divergence and convergence in psychophysiological markers.

In recent years, digital mental health has experienced a surge of interest in multimodal approaches to anxiety assessment, reflecting a growing demand for more comprehensive and precise evaluation methods (e.g., Aledavood et al., 2025; Choo et al., 2024; Sadeghi et al., 2024). These approaches combine different types of data, such as physiological signals with standardized scales, to provide a more comprehensive and ecologically valid view of emotional states. Multimodal integration enhances predictive accuracy and captures the complexity of anxiety more effectively than any single modality (Park et al., 2025; Senaratne et al., 2022). Among these inputs, physiological data are especially promising due to their objectivity, granularity, unobtrusiveness, and the growing availability of wearable sensors (Sano et al., 2018; Senaratne et al., 2022).

There has been growing interest in using technology, especially wearables, to detect anxiety and stress (e.g., Machhi and Shah, 2024, Al-Alim et al., 2024, Miranda et al., 2014, Elgendi and Menon, 2019, Abd-alrazaq et al., 2023). Exploration in anxiety indicators has centered around HR, electrodermal activity (EDA), and skin temperature (Edelmann & Baker, 2002; Kushki et al., 2013; Olesen et al., 2023; Shaukat-Jali et al., 2021). In the context of anxiety, these manifest as elevated HR, increased EDA, and fluctuations in skin temperature. Such physiological markers offer an objective lens for assessing anxiety, capturing both individual variability and common patterns across different anxiety presentations.

Data from wearable devices can efficiently be analyzed using machine learning (ML) techniques (Abd-alrazaq et al., 2023; De Arriba-Pérez et al., 2019; Shaukat-Jali et al., 2021; Zhai & Du, 2020). Within ML, Support Vector Machine (SVM) has been identified as the most effective algorithm, though Decision Trees, Random Forests, and K-Nearest Neighbors (KNN) have also demonstrated strong performance and are frequently employed (Shaukat-Jali et al., 2021). These are all types of supervised ML algorithms, where training data is pre-labeled according to class (e.g., baseline versus anxious state) and the algorithm learns from the training data with the goal to accurately predict the label for new, unseen test data based on the patterns learned from the training examples (Liu & Wu, 2012). A ML approach is particularly advantageous in cases where the volume of data is substantial, as in the case of data collected by wearables, rendering traditional statistical analysis computationally intensive and less feasible. Additionally, a supervised ML approach can identify subtle, intricate patterns that

may otherwise not be apparent using traditional statistical analysis alone. Prior literature has suggested that in 81% of cases, artificial intelligence broadly (including ML) was able to correctly classify individuals with and without anxiety, and it found better performance in detecting individuals without (92%) compared to those with anxiety (79%) (Abd-alrazaq et al., 2023). Further research is needed to differentiate and compare various types of anxiety (Abd-alrazaq et al., 2023), with certain types such as OCD and fear of needles remaining unexplored. Other anxiety-related symptoms, such as social anxiety, have been examined using ML techniques. A recent study found evidence that it is possible to detect both the presence of social anxiety (model accuracies between 97.54% - 99.48%) and its severity (model accuracies between 98.86% and 99.52%) using a ML approach (Shaukat-Jali et al., 2021). Furthermore, models were able to differentiate between baseline (not anxious), anticipatory anxiety, and reactive anxiety states (model accuracies between 95.18% and 98.10%). Given this, detecting anxiety using physiological markers from a wearable, utilizing a ML approach is promising. Yet critical gaps persist in understanding. A key open question is how physiological signatures vary across anxiety types, and whether these distinct patterns may nonetheless reflect shared mechanisms of arousal. Clarifying this could support the development of transdiagnostic models grounded in physiological data.

Both contamination OCD anxiety and needle anxiety have been understudied with respect to physiological signatures. A recent scoping review on the use of wearable and mobile technologies for evaluation and treatment of OCD found that wearables could be a helpful technology to accurately document the chronic, fluctuating concerns of OCD (Frank et al., 2023). Most of the passive-collection wearables included in the review used actigraphy to track physiological OCD symptoms, and this was found to generally match onto subjective reports (Frank et al., 2023). Passive data collection, such as through wearables or mobile phones, was also suggested to potentially involve a lower symptom burden than the retrospective recall involved in subjective measurements, such as traditional questionnaires (Frank et al., 2023). Thus, emerging evidence suggests that wearable technologies offer a promising, low-burden method for capturing symptoms that align well with subjective reports.

Nevertheless, though detecting anxiety via wearable physiological markers using ML is promising, key gaps remain—particularly in how signatures vary across anxiety types and whether shared arousal mechanisms exist (e.g., Bjelland et al., 2009; Knappe et al., 2013; Yarrington et al., 2022), which is crucial for developing transdiagnostic models. Only one feasibility study using physiological markers conducted with diagnosed adolescents (N = 9) and using an Empatica E4 wearable to measure blood volume pulse, skin temperature, EDA and HR predicted OCD episodes (Lønfeldt et al., 2023). These findings suggest that physiological markers can be used to detect OCD episodes that have occurred in the daily lives of adolescents diagnosed with OCD. To our knowledge, no study to date has used physiological markers to predict OCD-related anxiety in a general adult population.

Research on fear of needles is also lacking, particularly in adult populations. To date, there is no study on using physiological markers from wearables to predict needle anxiety in a general adult population. However, research using video data

and facial temperature in conjunction with ML techniques has predicted vasovagal response in individuals signed up to donate blood (Rudokaite et al., 2023, 2025). Findings demonstrated that it is possible to use facial responses during blood donation to predict vasovagal reactions (Rudokaite et al., 2025). Temperature changes in the forehead, chin, and under the nose in the waiting room prior to donating blood were most predictive of vasovagal reactions (Rudokaite et al., 2023). These promising results using facial temperature and ML to predict vasovagal responses in blood donors suggest that wearable physiological markers could help identify needle anxiety in the general population. Predicting needle anxiety using easily accessible physiological markers could lead to early intervention, increased vaccination adherence, blood donation, and uptake of routine medical care, reducing economic and public health burdens, as well as increasing positive individual health outcomes.

To gain a clearer understanding of anxiety, further research on physiological markers is necessary to identify both individual differences and shared patterns across anxiety symptomatologies. This study seeks to address this gap by comparing two relatively understudied forms of anxiety: contamination OCD anxiety (associated with sympathetic hyperactivation) and needle anxiety (associated with a documented vasovagal response). The aim is to explore how physiological signatures differ between these anxiety types and whether certain markers or marker combinations reflect shared features of anxious arousal. Expanding on prior research in physiological anxiety detection, we leverage wearable data and ML to examine whether anxiety states and severity levels can be accurately identified across both groups, and to examine whether distinct physiological signatures across anxiety types converge on shared patterns of arousal. Specifically, we investigate both differences in individual markers (HR, skin temperature, and EDA) and the potential for common combinations to accurately classify anxiety states. We also evaluate which ML models (SVM, Decision Tree, Random Forest, or KNN) achieve the highest classification accuracy.

6.2 Methods

6.2.1 Participants

This study uses data collected as part of two studies which were both preregistered on AsPredicted (accessible at https://aspredicted.org/r2bh-rncc.pdf and https://aspredicted.org/ykc7-62nr.pdf). The current study focuses solely on the physiological data collected in the two studies, while other measurements are analyzed and explored in other papers. Further detail on the participants and protocols of both studies, including the virtual environments, are explored in more detail in separate papers (Caltabiano, Burke et al., 2025b; Caltabiano, Voruganti et al., 2025). All participants were recruited via Instagram advertisements and posters placed around the main campus of Imperial College London, directing them to an online screening survey on Qualtrics.

A recent review of wearable artificial intelligence to detect stress reported a wide range of participant sample sizes from 5 to 652 (M = 77, SD = 149.5; Abdalrazaq et al., 2024). A similar study detecting anxiety using the same ML models

and the same wearable as the current study reported a sample size of 12 (Shaukat-Jali et al., 2021). Due to the sampling rate of the wearable device (e.g., 4 Hz for EDA), even a 12-participant sample size would result in approximately 172,800 data points over one hour for each physiological marker. Given prior literature, the feasibility of recruitment, the exploratory nature of this study, and limited research on this topic, we estimated that 15 participants in each symptomatology group would provide sufficiently powered results.

For the contamination anxiety group, the advertisements and posters inquired if potential participants found public toilets stressful and invited them to participate in a VR study exploring discomfort around contamination. Participants were required to be 18 years or older English speakers with contamination concerns (defined as either a score greater than 0 on the contamination subscale of the OCI-R or a response of "sometimes," "often," or "always" to at least one of the specifically devised contamination questions).

For the needle anxiety group, the advertisements and posters inquired if potential participants found needles and injections stressful, and invited them to participate in a VR study exploring discomfort around needles. Inclusion criteria was being 18 years or older, English speaking, and reporting a fear of needles, defined as scoring a 1 or higher on the SPQ blood-injection-injury subscale and/or scoring a 1 or higher on the MFS injections and blood subscale.

Exclusion criteria for both groups included reporting any condition precluding adherence to the measurement protocol (such as difficulty reading or writing), any uncorrected visual and/or auditory impairment affecting full participation in VR (use of corrective lenses or hearing aids was not a criterion for exclusion), presence or history of epilepsy, and history of severe motion sickness or dizziness. Participants were also excluded if they self-reported currently taking medication that affected HR, such as benzodiazepines, as this could artificially decrease anxiety responses. For the contamination anxiety group, they were also excluded if they reported a current or past diagnosis of OCD, or current or past treatment for OCD (including psychological and pharmacological therapies). For the needle anxiety group, they were excluded if they reported a current or past diagnosis of fear of needles, current or past treatment for fear of needles (excluding self-help), or a history of fainting from the sight of blood.

For the contamination anxiety group, 18 participants signed up and gave informed consent. Data from two participants were excluded due to hardware technical difficulties, leaving 16 participants in the final analysis. Participants who completed the study were entered into a raffle to win a £30 Amazon voucher.

For the needle anxiety group, 32 participants were recruited and gave informed consent. These participants received a £7 reimbursement as an Amazon voucher. Due to a fire alarm occurring during one participant's experimental session, their data from the start of the alarm to the end of the session was excluded, leaving their data from before the fire alarm. The difference in compensation between groups reflects differences in the original study designs. The contamination anxiety study offered a raffle entry as compensation due to greater difficulty in recruiting participants and more limited initial funding, whereas the needle anxiety study, which experienced fewer recruitment challenges, provided a fixed monetary reimbursement.

All study procedures were conducted in accordance with the ethical principles outlined in the World Medical Association's Declaration of Helsinki. Ethics approval was granted by the Research Governance and Integrity Team at Imperial College London (Reference numbers: 22IC7615 and 6577424).

6.2.2 Procedure

Participants who met the inclusion criteria and consented to take part in the study were invited to a lab session where they were asked to wear a wrist-wearable device to measure physiological data (i.e., EDA, HR, and skin temperature). This wearable was worn on the left wrist for all participants, in line with manufacturer recommendations ('E4 wristband', n.d.), and was turned on by the researcher to limit technical errors. Participants completed an online Qualtrics survey to provide baseline information on contamination anxiety or needle anxiety symptoms, depending on the group to which they were recruited. Participants were given a brief information sheet about exposure therapy and read a short script providing the context to the VR scenario they would experience shortly. Participants with contamination anxiety experienced a contaminated-appearing virtual environment of a public subway toilet, while participants with needle anxiety experienced an injection and blood-draw scenario in a virtual medical clinic environment. The scenarios were designed to elicit anxiety. Before entering the VR environment, participants were asked to select the skin color of their avatar. This was done to enhance the experience of embodiment in the virtual environment. Participants experienced two identical self-paced VR exposures and viewed a short neutral video between exposure sessions. The wearable collected physiological data through the entire session.

6.2.3 Measures

Demographics. Participants self-reported their age, sex, and whether their gender identity matched their sex assigned at birth.
Psychiatric Diagnoses. Participants self-reported any past or current psychiatric diagnoses.
OCD. Participants reported contamination-related anxiety using the OCI-R ($\alpha = 0.83$). The OCI-R (Foa et al., 2002) is a widely used self-report measure of OCD symptoms, comprising 18 items that assess symptoms across six subscales. Each item is rated on a 5-point Likert scale ranging from 0 ("not at all") to 4 ("extremely"). Total scores range from 0 to 72, where higher scores indicate greater related anxiety and distress.

To capture a full range of contamination-related anxiety, additional questions/statements were developed, answered on a 5-point Likert scale ranging from 1 ("Never") to 5 ("Always"): (1) "I experience anxiety or distress when I see a dirty toilet," (2) "How often do you find yourself *avoiding* public toilets due to fear or worry that they might be too dirty?", and (3) "How often do you find yourself *unable to use* public toilets due to fear or worry that they might be too dirty?"
Fear of Needles and Injections. Participants reported fear of needles and

injections symptoms using the blood-injection-injury subscale of the symptom severity SPQ ($\alpha = 0.74$). The SPQ subscale (Ovanessian et al., 2019) consists of two 14-item scales (one measuring symptom severity and one measuring life interference of these symptoms) on a 5-point Likert scale, ranging from 0 (no fear/no interference) to 4 (extreme fear/extreme interference). Total scores for symptom severity on the subscale range from 0 to 56, where higher scores indicate greater fear. Only the symptom severity subscale was used for this study, as the life interference subscale was not relevant to our research questions.

6.2.4 Equipment & Environments

Wearable. Physiological data measurements were taken by an Empatica E4 device. The clinical device is a research-grade wristband wearable with multiple sensors that simultaneously collect various physiological data including HR, EDA, and skin temperature ('E4 wristband', n.d.). It is one of the most commonly used wearable devices for detecting anxiety in previous similar studies (Abd-alrazaq et al., 2023). The E4's default units and sampling rates are: EDA measured in microSiemens at 4 Hz, HR measured in beats per minute at 1 Hz, and skin temperature measured in degrees Celsius at 4 Hz.

Virtual reality equipment & environments. Amelia by XR Health's public toilet VR environment, which depicts a contaminated public toilet in a subway area, was used to elicit contamination anxiety (Figure 6.1). The scenario begins with the participant standing outside the door of a public toilet. The participant sees other individuals by the cubicles and the sink upon entering. The participant is able to enter the cubicle in front of them and interact with the toilet-related elements (e.g., toilet lid, toilet paper, toilet brush), and can sit down on the toilet (the participant can simultaneously sit in a chair in the real world to mirror their position in VR). The participant is subsequently placed in front of the sink and able to wash their hands in the virtual scenario.

The participants' VR environments are controlled through Amelia by XRHealth's online platform, where the following actions can be taken: open the entrance door, open the cubicle door, touch the wall while standing inside the cubicle, lower the toilet lid, flush the toilet, touch the wall while sitting on the toilet, take toilet paper, touch the toilet brush, and wash hands. In this study, participants completed the actions in the given order at their own pace. When asked to sit on the virtual toilet, a real-life chair was provided to heighten the sense of immersiveness in the virtual environment.

Figure 6.1. Screenshot of the VR environment depicting a dirty public toilet

To elicit needle anxiety, the participants engaged in Amelia by XR Health's environment depicting a medical clinic (Figure 6.2). Participants began sessions by sitting in a clinic waiting room, where other patients can be heard discussing their recent injections and characterizing them as painful. A clinician escorted the participant into the clinic room, where they were exposed to vials and other blood-draw equipment as the clinician prepared for the appointment. The participant sat in the patient chair (mirrored by sitting in a physical chair in the real world) and sequentially experienced a virtual finger-prick, injection, single-vial blood draw, and multi-vial blood draw.

This VR environment was also controlled through Amelia by XRHealth's online platform. Participants completed the actions in the given order at their own pace. To limit VR sickness and heighten the sense of plausibility and immersiveness of the virtual environment, as well as maintain safety in the case of syncope, participants were asked to remain seated during the VR session.

All VR software was run on a PICO G2 HMD VR headset.

6.2.5 Data Analysis

Missing physiological data were addressed using casewise retention. Due to the self-paced nature of the VR exposure sessions, the duration of data collection varied across participants. This, combined with technical issues such as brief signal dropouts or inconsistent start times, made it infeasible to calculate a uniform percentage of missingness across participants. No missing data were recorded for self-report measures.

Data preprocessing. For ease of analysis, to match the sampling rate of EDA and skin temperature, HR data was first upsampled from 1 Hz to 4 Hz. A Moving Average Filter was applied to remove noise and reduce model overfitting (Dougherty, 2013; Zhang et al., 2016). A range correction method was applied to participant EDA to remove inter-individual differences while preserving vari-

Figure 6.2. Screenshot of the VR environment depicting a finger-prick blood test

ation with the EDA range, as this has been proposed to better capture accurate physiological activation (Lykken & Venables, 1971). The use of the Moving Average Filter and EDA range correction method in preprocessing data to use ML techniques to detect anxiety, along with their respective mathematical formulations, are described in more detail by Shaukat-Jali et al. (2021).

To allow physiological signals to return to baseline and remove artifacts (e.g., due to adjusting the wearable post-activation) the first two minutes of data were excluded for all participants.

Figure 6.3. Labeling for experiment 1

Baseline 1	**Anxious 1** (VR exposure)	**Baseline 2** (neutral video)	**Anxious 2** (VR exposure)

As Experiment 1 examines which physiological marker accurately detects anxiety in the given symptomatology using ML models, participants' data were split into baseline and anxious states (Figure 6.3). Because the VR exposures were self-paced, the duration of anxious phases varied across participants. Given that Experiment 2 investigates whether physiological markers can accurately distinguish anxiety severity within the targeted symptom domains, participants were grouped by high or low symptom severity. All baseline phases were excluded to focus exclusively on periods of anxious arousal (Figure 6.4). For contamination anxiety, based on prior literature a score of ≥ 27 on the OCI-R was used as the threshold for symptom severity (Abramovitch et al., 2020). For needle anxiety, ≥ 20 on the SPQ was used to indicate high symptom severity, based on Receiver Operating Characteristic (ROC) analysis identifying optimal sensitivity/specificity for needle anxiety, though this is not a formal diagnostic cutoff (Ovanessian et al., 2019).

All participant data were then combined and features were standardized to have zero mean and unit variance, which is recommended for algorithms such as

Figure 6.4. Labeling for experiment 2

Anxious 1 (VR exposure)	**Anxious 2** (VR exposure)

SVM (Géron, 2019).

Data processing. Four classification algorithms were explored for each experiment and symptomatology: KNN, SVM, Random Forest, and Decision Tree. Hyperparameter tuning was used to find the most optimal parameters for each model. The trained models were evaluated using 10-fold cross-validation, which is a commonly used method in the field (Géron, 2019). In k-fold cross-validation, the data is split into k-folds, so that k-1 folds can be used for training the model and 1 fold can be used for testing. A 5-fold cross-validation, a commonly used alternative, was also tested but produced slightly lower accuracy compared to the 10-fold cross-validation, likely because 10-fold provides more training data per iteration, which can lead to more stable and generalizable model performance in small datasets (Table C.1, Table C.2, Table C.3, Table C.4).

To compare models, accuracies and F1 scores were reported. Accuracy percentages reflect the overall correctness of classification, while F1 scores use the harmonic mean of precision and recall in the given model to evaluate its performance in classification (Emmert-Streib et al., 2023). Due to the exploratory nature of this study and the minor class imbalances for both symptomatologies, a confusion matrix approach was not used for accuracies.

6.3 Results

6.3.1 Contamination OCD Anxiety

The contamination OCD symptom group included 16 participants (6 females, 9 males, and 1 who preferred not to disclose). 87.5% of participants reported a gender identity that matched their sex assigned at birth, while the remaining 12.5% reported a different gender identity. Ages ranged from 18 to 32 years ($M = 21.75$, $Mdn = 20.50$, $SD = 3.86$). Contamination OCD symptoms, as measured by the OCI-R, ranged from 8-47 ($M = 29.06$, $Mdn = 32.50$, $SD = 11.65$), out of a max score of 72. 4 participants reported having prior VR experience.

6.3.1.1 Experiment 1: Detecting anxiety states

As shown in Table 6.1, skin temperature was the most accurate single physiological marker for distinguishing between anxious and baseline states (74.69%, SD = 0.34), using a KNN model. HR resulted in lowest accuracies (68.00%, SD = 0.39). Among combined markers, skin temperature and EDA achieved the highest accuracy (92.96%, SD = 0.19), as shown in Table 6.2, also using KNN. Across all combinations, KNN consistently outperformed other classifiers.

Table 6.3 presents the 10-fold cross-validation results. KNN was demonstrated to be the highest performing ML model, achieving near-perfect classification with an accuracy of 99.16% (SD = 0.05) and an F1 score of 0.99 (SD = 0), followed by SVM with an accuracy of 90.55% (SD = 0.25) and an F1 score of 0.88 (SD = 0).

Table 6.1. Highest cross-validation results for contamination OCD symptoms per single physiological marker

Physiological Marker	Highest Performance Classifier	Accuracy % (SD)
Experiment 1		
HR	KNN	68.00 (0.39)
Skin Temperature	KNN	74.69 (0.34)
EDA	Decision tree & Random forest	68.29 (0.28)
Experiment 2		
HR	Decision tree & Random forest	68.93 (0.70)
Skin Temperature	KNN	79.82 (0.66)
EDA	KNN	76.55 (0.99)

Table 6.2. Highest cross-validation results for contamination OCD symptoms per physiological marker combination

Physiological Marker	Highest Performance Classifier	Accuracy % (SD)
Experiment 1		
HR & Skin Temperature	KNN	86.01 (0.26)
HR & EDA	KNN	81.14 (0.39)
Skin Temperature & EDA	KNN	92.96 (0.19)
Experiment 2		
HR & Skin Temperature	KNN	86.91 (0.36)
HR & EDA	KNN	82.56 (0.65)
Skin Temperature & EDA	KNN	94.96 (0.37)

In contrast, Random Forest had the lowest accuracy of 67.03% (SD = 0.49) with an F1 score of 0.40 (SD = 0.02), indicating weaker ability to correctly identify anxiety states.

Table 6.3. 10-Fold cross-validation results for contamination OCD symptoms experiment 1

Model	Accuracy % (SD)	F1 Score (SD)
SVM	90.55 (0.25)	0.88 (0)
KNN	99.16 (0.05)	0.99 (0)
Decision Tree	71.12 (0.68)	0.63 (0.01)
Random Forest	67.03 (0.49)	0.40 (0.02)

6.3.1.2 Experiment 2: Classifying anxiety severity

Participants were categorized into high and low severity groups using a cutoff of ≥ 27 on the OCI-R. The resulting class imbalance (1:2) was mild and did not require sampling correction such as applying the Synthetic Minority Oversampling Technique or under-sampling (Leevy et al., 2018; Provost, 2000).

As with Experiment 1, skin temperature was also the highest accuracy physiological marker when differentiating between severity of contamination OCD symptoms (79.82%, SD = 0.66) using a KNN model, while HR resulted in the lowest accuracy (68.93%, SD = 0.70) using Decision Tree and Random Forest (Table 6.1). Skin temperature and EDA were the combined markers with the highest accuracy (94.96%, SD = 0.37) using KNN (Table 6.2).

As shown in Table 6.4, KNN again demonstrated highest performance with an accuracy of 99.73% (SD = 0.10) and an F1 score of 1.00 (SD = 0), closely followed by SVM with an accuracy of 98.04% (SD = 0.21) and an F1 score of 0.97 (SD = 0). Random forest again had the lowest accuracy (68.75%, SD = 0.02) and had a poor F1 score of 0 (SD = 0), indicating an inability to effectively distinguish between anxiety severity levels.

Table 6.4. 10-Fold cross-validation results for contamination OCD symptoms experiment 2

Model	Accuracy % (SD)	F1 Score (SD)
SVM	98.04 (0.21)	0.97 (0)
KNN	99.73 (0.10)	1.00 (0)
Decision Tree	85.15 (0.75)	0.76 (0.01)
Random Forest	68.75 (0.02)	0.00 (0)

6.3.2 Needle Anxiety

The needle anxiety group comprised 25 females and 7 males. 96.88% identified their gender as the same as the sex they were assigned at birth. Participants were aged 18-48 ($M = 25.31$, $Mdn = 21$, $SD = 8.60$). Needle anxiety as measured by the SPQ ranged from 24 to 62 ($M = 41.06$, $SD = 9.60$). 13 participants in the experimental group reported having prior VR experience.

6.3.2.1 Experiment 1: Detecting anxiety states

Table 6.5 shows that skin temperature was again the most accurate single physiological marker (67.67%, SD = 0.26), using a KNN model. HR performed poorest (54.66%, SD = 0.17). As with contamination OCD symptoms, skin temperature and EDA were the combined physiological markers with the highest classification accuracy (92.31%, SD = 0.13), with KNN (Table 6.6). Notably, when using a combination of two physiological markers, KNN again was consistently the highest performance classifier.

Table 6.5. Highest cross-validation results for needle anxiety per single physiological marker

Physiological Marker	Highest Performance Classifier	Accuracy % (SD)
Experiment 1		
HR	Decision tree & Random forest	54.66 (0.17)
Skin Temperature	KNN	67.67 (0.26)
EDA	KNN	58.72 (0.31)
Experiment 2		
HR	Decision tree & Random forest	68.78 (0.48)
Skin Temperature	KNN	79.13 (0.46)
EDA	Decision tree & Random forest	73.50 (0.49)

Table 6.6. Highest cross-validation results for needle anxiety per physiological marker combination

Physiological Marker	Highest Performance Classifier	Accuracy % (SD)
Experiment 1		
HR & Skin Temperature	KNN	82.67 (0.30)
HR & EDA	KNN	75.68 (0.2 17)
Skin Temperature & EDA	KNN	92.31 (0.13)
Experiment 2		
HR & Skin Temperature	KNN	86.34 (0.23)
HR & EDA	KNN	80.71 (0.78)
Skin Temperature & EDA	KNN	95.28 (0.38)

According to Table 6.7, KNN was the top-performing model in the 10-fold cross-validation (99.26%, SD = 0.06; F1 = 0.99, SD = 0). SVM followed with 83.46% accuracy (SD = 0.14) and an F1 score of 0.83 (SD = 0). Random Forest remained the weakest performer (62.17%, SD = 0.33; F1 = 0.59, SD = 0.01).

Table 6.7. 10-Fold cross-validation results for needle anxiety experiment 1

Model	Accuracy % (SD)	F1 Score (SD)
SVM	83.46 (0.14)	0.83 (0)
KNN	99.26 (0.06)	0.99 (0)
Decision Tree	64.20 (0.28)	0.57 (0)
Random Forest	62.17 (0.33)	0.59 (0.01)

6.3.2.2 Experiment 2: Classifying anxiety severity

Participants were classified into severity groups based on a cutoff of ≥ 20 on the SPQ. The resulting group imbalance (11:5) was mild and did not require correction (Leevy et al., 2018; Provost, 2000).

In Experiment 2, skin temperature was again the most accurate single physiological marker for differentiating between high and low severity of needle anxiety (79.13%, SD = 0.46), using a KNN model (Table 6.5). Similarly to Experiment 1, HR resulted in lowest accuracies (68.78%, SD = 0.48). Again, skin temperature and EDA were the combined markers with the best performance (95.28%, SD = 0.38) using KNN. KNN was the highest performance classifier when using a combination of two physiological markers for Experiment 2 as well.

In the 10-fold cross-validation, KNN achieved the highest performance among the ML models, with an accuracy of 99.34% (SD = 0.14) and an F1 score of 1.00 (SD = 0). The SVM model ranked second, demonstrating a strong model performance with an accuracy of 95.77% (SD = 0.32) and an F1 score of 0.97 (SD = 0). By comparison, Random forest again had the lowest accuracy of 68.75% (SD = 0) with an F1 score of 0.81 (SD = 0), suggesting a more limited effectiveness in classifying needle anxiety severity.

Table 6.8. 10-Fold cross-validation results for needle anxiety experiment 2

Model	Accuracy % (SD)	F1 Score (SD)
SVM	95.77 (0.32)	0.97 (0)
KNN	99.34 (0.14)	1.00 (0)
Decision Tree	74.37 (0.40)	0.84 (0)
Random Forest	68.75 (0)	0.81 (0)

6.4 Discussion

This study aimed to investigate whether physiological markers collected via a wearable device could accurately detect anxiety states and differentiate severity across two distinct symptomatologies: contamination OCD anxiety and needle anxiety. These two anxiety types were chosen because they are both highly prevalent and functionally impairing, yet underrepresented in physiological and wearable-based anxiety research. They also differ markedly in their autonomic signatures, with contamination OCD anxiety typically associated with sympathetic arousal and needle anxiety characterized by vasovagal responses. This makes them ideal test cases for examining how physiological signatures of anxiety differ across symptom presentations that vary in autonomic profile. At the same time, the study examines whether any overlapping patterns of arousal could be identified, particularly in relation to skin temperature and EDA. Examining both differences and similarities supports a transdiagnostic, dimensional view of anxi-

ety and addresses a key gap in the literature on passive, wearable-based detection in real-world cases beyond commonly studied anxiety types.

6.4.1 Physiological Markers

Our findings demonstrate that skin temperature was the most consistent and reliable single physiological marker across both anxiety types and for detecting anxiety states as well as classifying severity. ML models using skin temperature outperformed those relying solely on HR or EDA, particularly when using the KNN classifier. This suggests that skin temperature may be a particularly sensitive indicator of physiological arousal related to anxiety, even across symptom profiles that differ in presentation.

Interestingly, HR alone consistently produced the lowest classification accuracies, especially for needle anxiety. This result may be attributable to the vasovagal characteristics often associated with needle-related anxiety, which can involve seemingly paradoxical drops in HR, thereby reducing its reliability as a unidirectional anxiety marker. Although HR is commonly regarded as a primary indicator of anxiety, this study aligns with a growing body of literature (e.g., Clarke et al., 2014; Pittig et al., 2013) that suggests HR may not serve as a consistent or reliable marker across all anxiety types. In contrast, skin temperature appears to track anxiety-induced changes in autonomic activation more robustly, potentially because it reflects both sympathetic arousal and thermoregulatory physical responses.

Combinations of physiological markers further improved classification accuracy, with the pairing of skin temperature and EDA outperforming all other combinations. These findings reinforce the idea that multimodal physiological data can capture more nuanced and detailed aspects of anxiety-related responses. EDA, while not the top performer alone, likely adds complementary information about sympathetic nervous system activity that enhances the discriminative power of skin temperature when used in combination.

Our findings align with previous research identifying skin temperature as one of the most robust physiological indicators of anxiety in individuals with subclinical social anxiety (Shaukat-Jali et al., 2021). Similar to the current study, their use of a KNN model yielded high accuracy, further supporting the utility of combining skin temperature and EDA for anxiety detection across different symptom domains. The current study further expands previous findings by contributing to the growing literature by including two underrepresented symptomatologies–needle anxiety and contamination anxiety–helping to fill a gap in anxiety research where these subtypes are often excluded or overlooked. The replication of these patterns for social anxiety, as well as the current contamination and needle anxiety groups, suggests that skin temperature, particularly when combined with EDA, may represent a generalizable physiological signature of anxiety detectable via wearable technologies.

Our findings show that although contamination OCD and needle anxiety engage different autonomic systems, they can produce physiological signatures that overlap in certain measurable ways, particularly in skin temperature and EDA. The consistency of these findings across diverse anxiety symptomatologies sug-

gests a degree of generalizability in how these physiological markers signal anxious states. Despite physiological differences between contamination anxiety (typically associated with increased sympathetic activity) and needle anxiety (typically linked with vasovagal responses involving parasympathetic over-activation), the same physiological features–skin temperature and EDA–proved effective across both. This convergence may reflect the fact that these markers are sensitive to any disruption in autonomic balance, regardless of the direction of the response. Skin temperature, for example, is modulated by both sympathetic vasoconstriction and parasympathetic withdrawal, and may drop during both hyperarousal and vasovagal states due to changes in peripheral blood flow (Kreibig, 2010). Similarly, EDA reflects sympathetic nervous system activity but may still show variation during parasympathetic-dominant states, especially when preceded by anticipatory arousal (Callara et al., 2021). Thus, rather than indicating a single, uniform mechanism, these markers may reflect dynamic shifts in autonomic regulation. These shifts, involving activation, withdrawal, or fluctuation, are common across acute anxiety states, regardless of the specific autonomic pathway involved (Hyde et al., 2019). This interpretation aligns with model proposed by Berntson et al. (1994), which states that autonomic responses are not binary but rather involve complex, interactive contributions from both sympathetic and parasympathetic systems. This echos recent work that found that although specific anxiety disorders may differ in absolute reactivity, they often share core psychophysiological patterns, including elevated physiological sensitivity to threat cues (Hyde et al., 2019). These frameworks may help explain why shared physiological markers, such as skin temperature and EDA, can be detected across divergent anxiety types that differ in outward expression but may converge in underlying autonomic dynamics and threat processing systems.

6.4.2 Machine Learning Models

Across both contamination and needle anxiety groups, certain ML models demonstrated high accuracy in classifying anxious versus baseline states and differentiating high versus low severity during anxious states. Notably, the KNN algorithm consistently outperformed other models in both anxiety types and across both experimental conditions, suggesting its robustness for classifying physiological data in this context. This suggests that KNN has a better ability to effectively capture subtle, non-linear patterns in these types of anxiety datasets, compared to other algorithms tested. The SVM algorithm also consistently performed well.

In contrast, the Random Forest and Decision Tree models exhibited poorer performance. This may seem counterintuitive given Random Forest is an ensemble learning method often favored for its robustness to noise and overfitting (Breiman, 2001). However, its performance may decline when the number of independent samples is low (despite a high volume of time-series data points) as observed in this study, particularly within the contamination anxiety group (Cavalheiro et al., 2023). Although each participant generated thousands of data points through high-frequency sampling, these are not independent observations. The observations exhibit high autocorrelation and are clustered within individuals, limiting the variability and generalizability that ensemble models like Random

Forest and Decision Trees typically rely on for optimal performance (Breiman, 2001; Cavalheiro et al., 2023).

Furthermore, Random Forest relies on random sampling of both features and instances to train multiple decision trees (Breiman, 2001). In small, relatively homogeneous samples, this can produce unstable trees and obscure more subtle, consistent physiological patterns. Additionally, Random Forest tends to smooth out fine-grained signals, potentially also overlooking nuanced variations of physiological anxiety responses that are critical to identifying anxiety states and/or severity (Xu et al., 2023). This contrasts with instance-based methods (e.g., KNN) or margin-based classifiers (e.g., SVM), which are often better suited to datasets with limited participant diversity but have extensive within-subject granularity.

Our findings are consistent with prior literature showing strong performance of ML techniques, particularly KNN, in detecting stress and anxiety using wearables (e.g., (Abd-alrazaq et al., 2023, 2024; Shaukat-Jali et al., 2021)). The consistency of KNN's performance across multiple studies suggests that it may be particularly suited for exploratory small-sample wearable research, where the focus is more on individual variation rather than group-level generalization.

6.4.3 Theoretical and Clinical Implications

The current study provides evidence that different types of anxiety can be detected with high accuracy using similar ML techniques, despite differing in physiological presentation (e.g., vasovagal features in needle anxiety versus sympathetic activation in contamination anxiety). This finding supports the hypothesis that the underlying physiological patterns of anxiety may share a common, detectable structure even across anxiety subtypes with divergent symptom profiles (Hyde et al., 2019). This shared structure arises not from identical autonomic pathways, but from similar patterns of autonomic disruption—where distinct physiological mechanisms produce comparable changes in physiological markers. In contamination OCD anxiety, this disruption may involve sympathetic hyperactivation (e.g., increased EDA and vasoconstriction), whereas in needle anxiety, it may involve anticipatory sympathetic arousal followed by parasympathetic dominance (e.g., vasovagal response) (Kreibig, 2010). Despite these differences, both symptom profiles result in detectable changes in peripheral physiology, particularly in skin temperature and EDA, which may reflect a shared dysregulation of threat-response systems rather than uniform activation patterns.

The consistent role of skin temperature and EDA across both anxiety types suggests that certain physiological markers may reflect a transdiagnostic fingerprint of anxiety-related arousal, by capturing shifts in autonomic balance that are present across different anxiety types, even when those shifts arise from distinct mechanisms. For example, contamination OCD anxiety may involve increased sympathetic drive, while needle anxiety may involve parasympathetic overactivation, yet both can result in measurable disruptions in thermoregulation and EDA detectable by wearable devices. This suggests that even when the underlying autonomic mechanisms differ, a common physiological signal may arise from overlapping dimensions of threat processing or subjective distress. This aligns with dimensional models of psychopathology, such as the National Institute of

Mental Health's Research Domain Criteria (Cuthbert, 2015; 'Research Domain Criteria (RDoC) - National Institute of Mental Health (NIMH)', n.d.), which emphasize shared physiological processes across traditional diagnostic boundaries.

Our results suggest potential clinical utility in using wearables to support early identification and differentiation of subclinical anxiety. Subthreshold anxiety disorders, which often go undetected in traditional healthcare settings, can nonetheless cause significant impairment (Angst et al., 1997; Bjelland et al., 2009; Konstantopoulou et al., 2020; Lang & McTeague, 2009). Gaining a deeper understanding of physiological anxiety markers could pave the way for early intervention, potentially reducing the risk of progression to clinical diagnosis. More broadly, physiological markers offer a passive and objective means of augmenting traditional self-report measures, which are often limited by recall biases, literacy barriers, and stigma. The successful application of a ML approach to passively collected physiological data provides a promising pathway for scalable screening tools. Although wearable technologies may raise concerns about intrusiveness or privacy, their use alongside self-report instruments may be especially valuable in underserved populations where barriers to traditional assessment are common. Notably, our findings raise important theoretical implications: if distinct anxiety types exhibit similar physiological signatures, yet differ in their behavioral manifestations and/or lived experience of symptoms, this suggests a shared underlying arousal mechanism that diverges downstream. Conversely, if physiological signatures diverge while subjective experiences converge, this points to multiple autonomic pathways leading to a common felt experience of anxiety. Both interpretations merit further investigation and support a nuanced, multidimensional model of anxiety.

Moreover, the capacity to distinguish between severity levels within anxious states provides a valuable tool for tailoring interventions. For example, individuals with higher physiological reactivity may benefit from more intensive exposure-based interventions or adjunctive strategies, such as biofeedback, while those with milder profiles may respond well to self-guided or digital interventions. Longitudinal tracking of physiological markers could also allow clinicians to monitor treatment progress or relapse risk in a continuous, personalized manner.

6.4.4 Limitations and Future Directions

Despite the large volume of data collected per participant, this study is limited by its relatively small number of unique participants. In ML, particularly for ensemble approaches such as Random Forest, performance tends to improve with greater heterogeneity in the training data. While high-frequency sampling yields hundreds of thousands of data points per participant, these data are highly autocorrelated and the number of independent observations remains small. However, this sampling approach is consistent with norms in psychophysiological research using wearable devices, where each participant generates time series data that allows for robust within-subject modeling. In this study, all data were collected using a clinically validated, research-grade wearable. To ensure signal quality while managing resource constraints, a single device was used sequentially across participants rather than distributing multiple lower-cost wearables. This design

choice provided high-fidelity physiological data but necessarily slowed the pace of data collection. Given these constraints, the sample size reflects a methodological trade-off common in high-resolution physiological studies. Future research should aim to replicate these findings in larger and more demographically diverse samples, including clinical populations.

Another limitation of the study involves class imbalance within the high versus low symptom severity groups, particularly in the needle anxiety condition. Although the imbalance was relatively mild and did not necessitate resampling techniques (e.g., Synthetic Minority Oversampling Technique or undersampling), it may still have introduced subtle biases during model training, especially in algorithms like Decision Trees and Random Forests, which can be more sensitive to imbalanced class distributions. Even in KNN and SVM, which performed robustly overall, class imbalance may have skewed decision boundaries or affected generalizability to more balanced populations. Future research with larger and more evenly distributed symptom severity groups could help validate the stability and fairness of model performance.

While the use of skin temperature and EDA yielded strong classification results, individual variability in physiological baselines (e.g., skin conductance reactivity or cardiovascular fitness) may have introduced noise or bias. Future research would benefit from collecting information about potential covariates (e.g., BMI and fitness level) to better account for individual differences in physiological responsiveness. Additionally, the current study focused on three physiological markers commonly studied in anxiety. Future research could also explore whether combining these with other physiological markers (e.g., facial temperature, respiration, or movement patterns) might enhance classification performance. Finally, although the study implemented 10-fold cross-validation, which is a common method in this field, future work should also consider participant-level holdout methods to better estimate out-of-sample generalizability.

Despite these limitations, the study has several strengths. It is the first to apply ML models to physiological markers across two distinct and understudied anxiety types using standardized VR exposures via a clinically-graded wearable. The combination of VR and wearables represents a novel and ecologically valid approach to eliciting and measuring anxiety in a controlled yet realistic context. Our study strengthens the case for using instance-based models such as KNN in small, high-density datasets typical of wearables, contributing practical guidance to the growing field of affective computing. Furthermore, the successful classification of both anxiety states and severity levels based on passive data supports the feasibility of scalable, tech-based approaches to mental health detection and monitoring.

6.4.5 Conclusion

This study provides compelling evidence that physiological markers, particularly skin temperature and EDA, can accurately detect anxiety states and differentiate severity across distinct anxiety symptomatologies using ML techniques. The consistent performance of these markers across both contamination and needle anxiety highlights their potential as transdiagnostic indicators, even across anxi-

ety types with divergent physiological mechanisms. Our findings not only contribute to theoretical understanding of how physiological signatures of anxiety vary across distinct presentations, but also highlight that certain physiological markers may generalize across symptom types. This offers promising avenues for developing objective, scalable, and accessible tools for early detection and personalized intervention. As wearable technologies become increasingly integrated into daily life, leveraging these tools for mental health monitoring can transform how anxiety is identified and managed in both clinical and non-clinical settings. This shift holds the potential to enable earlier detection, personalized intervention, and a more proactive approach to mental health care on a global scale.

7 General Discussion: Considerations for the Future Design of Virtual Reality Exposure-Based Therapy

7.1 Summary and Integration of Findings

The present research provides early-phase evidence that VRET is an acceptable and potentially effective tool for addressing subclinical anxiety symptoms related to contamination-based OCD and fear of needles. The findings across Chapter 3 to Chapter 6 represent a progression from symptom characterization to intervention evaluation and technological considerations. Chapter 3 provided a descriptive overview of the severity, impact, and experience of subclinical contamination-featured OCD and fear of needles symptoms. This context helped to frame the relevance and appropriateness of the VRET interventions investigated in Chapter 4 and Chapter 5, which used commercially available VR applications to deliver VRET in these domains. Although the virtual environments themselves were pre-designed, the participant experiences within them were consistent with the symptom patterns identified earlier. Both case studies demonstrated that immersive exposure can induce anxiety responses sufficient for therapeutic purposes while maintaining high levels of participant engagement and acceptability. Chapter 6 extended this work by exploring physiological markers of anxiety during exposure, indicating the potential for future VRET systems to incorporate adaptive features based on real-time data. Taken together, these chapters contribute to a broader understanding of how VRET can be applied in subclinical anxiety contexts. It is worth acknowledging that the two case studies differ in several design features that complicate direct integration of their findings. Chapter 4 employed a single-arm design with no comparison group, whereas Chapter 5 included an online comparison group, though without randomization. The outcome measures also differed across studies, reflecting the distinct symptom profiles of the two conditions. These differences mean that the two case studies are not directly comparable in terms of effect sizes or statistical conclusions, and no attempt is made here to synthesize findings as if they were. Instead, the value of studying both conditions lies in what they share: both demonstrated that a single session of HMD VRET can reliably elicit anxiety responses sufficient for therapeutic exposure, and both found that participants rated the experience as acceptable and usable. These convergent findings across two mechanistically distinct anxiety presentations strengthen the case that VRET is a generalizable delivery modality for subclinical anxiety, even where the specific symptom profiles and study designs differ. The divergent findings, particularly the difference in symptom reduction outcomes between the two case studies, are informative in their own right, suggesting that single-session protocols may have differential effects depending on the anxiety type and pointing toward the need for condition-specific protocol optimization in future research.

7.1.1 Industry Partnership: Role of XRHealth and Independence of Research

This project was conducted with industry partnership support from XRHealth (previously Amelia by XRHealth), as described in Chapter 1. XRHealth provided the VR hardware, software platforms, and technical support used in both case studies, as well as access to commercially deployed VR environments for contamination-related OCD (Chapter 4) and fear of needles (Chapter 5). The exposure sequences within these environments were developed by XRHealth's clinical team and were not designed by the candidate; the specific design rationale underlying these sequences is not fully documented in the published literature, as noted in the methods sections of both case study chapters. XRHealth had no involvement in the design of the research questions, study protocols, data collection procedures, data analysis, or interpretation of results. All data were collected, managed, analyzed, and reported independently by the candidate and supervisory team. XRHealth did not review or approve manuscripts or thesis chapters prior to submission. The industry partnership was limited to the provision of hardware, software, and technical support. A potential conflict of interest exists insofar as XRHealth, as the provider of the VR platforms evaluated, has a commercial interest in findings that support the use of their products. This is acknowledged transparently. To manage this, all analytical decisions were made independently of XRHealth, and the candidate retained full control over the interpretation and reporting of findings. The limitations associated with using commercially developed environments whose design rationale is not fully documented are discussed in the methods sections of both case study chapters and are reflected in the caution with which conclusions are drawn throughout this thesis.

This thesis makes a novel contribution to the digital mental health literature by focusing on subclinical anxiety, a population that is often underserved in research and excluded from formal interventions. Rather than assuming clinical treatment is always needed, this work explores whether virtual reality could serve as a scalable and acceptable tool for early intervention and prevention of symptom escalation. While most studies on VRET have targeted individuals with diagnosed anxiety disorders, this project extends its application to those whose symptoms cause meaningful distress but fall below diagnostic thresholds. Additionally, given that some participants may meet diagnostic thresholds, the findings may also have implications for individuals at the boundary between subclinical and clinical anxiety. In addition to exploring feasibility, the thesis also examines acceptability, an essential factor in determining whether users are willing to engage with emerging therapeutic formats. The findings highlight that individuals with subclinical anxiety symptoms are open to engaging with VRET, and that commercially available VR environments are perceived as credible and usable. By using off-the-shelf hardware and software, this research ensures that the results are grounded in realistic, scalable solutions rather than bespoke laboratory setups. This enhances the translational value of the work and underscores its relevance for real-world mental health support. Moreover, these findings hold significant implications for both individual-level mental health care and broader public health strategies.

At the individual level, VRET offers a promising solution for individuals who experience barriers to traditional therapy. These may include logistical barriers such as transportation or time off work, psychological barriers such as stigma or fear of in vivo exposure, and structural barriers such as a lack of trained clinicians. In the current research, participants consistently reported that they found VRET acceptable and engaging. They also demonstrated physiological responses, including elevated HR, skin temperature, and EDA, indicating that exposure was occurring at a level sufficient for therapeutic processing.

On a public health level, the scalability and adaptability of VRET suggest that it could play a role in reducing the burden of untreated or subclinical anxiety in the general population. Individuals with subclinical symptoms often go untreated, yet research has shown they are at elevated risk of progressing to full-threshold disorders. Interventions like VRET, which do not require a formal diagnosis to access, can help democratize mental health care by offering viable therapeutic options for those who may not otherwise seek or receive support. For instance, an individual with a mild but distressing fear of needles who avoids vaccinations may never enter the clinical system, yet could benefit from a self-guided VRET module delivered through an affordable headset. While previous work has examined the impact of fear of needles on healthcare avoidance, there appears to be no research exploring whether such fear might act as a confounding factor in avoidance attributed to conspiracy beliefs or mistrust in medical systems. This represents a potential gap in the literature, as some individuals who cite alternative explanations for health problems or express skepticism toward medical interventions may also experience underlying phobic anxiety toward needles. Future research could investigate whether addressing needle fear might indirectly reduce certain forms of healthcare avoidance linked to such attitudes.

Beyond individual therapy, VR is beginning to support new forms of communal care. Group therapy sessions are now being piloted within VR environments, enabling users to interact in shared therapeutic spaces (e.g., Anderson et al., 2017; Arnfred et al., 2021; Dilgul et al., 2021; Ngai et al., 2015). These allow for exposure exercises to be conducted with others who share similar anxieties, reducing isolation and enhancing motivation. Peer counseling groups for depression and anxiety are also being explored in social VR platforms, where users meet in facilitated sessions to share strategies and emotional support (Robinson et al., 2025). As these peer counseling groups are facilitated by trained non-clinicians rather than licensed mental health professionals, individuals in need of support are not constrained by the availability of clinicians, an important consideration in light of the widespread and ongoing global shortage of mental health providers. Furthermore, the virtual nature of these peer counseling groups eliminates the need for geographic proximity to clinical facilities or mental health centers, thereby reducing barriers related to travel, infrastructure, and local service availability. These developments may be particularly beneficial for underserved populations, those who face stigma in their local communities, or those who are not formally diagnosed yet still experience significant anxiety-related distress.

Various types of training and education are increasingly taking place within virtual reality, which offers a powerful and immersive way to learn by doing (Xie et al., 2021). VR-based training programs are being developed for first responders,

surgeons, soldiers, and students, allowing them to practice following procedures, operate technical systems, and respond to emergency scenarios. Many companies (e.g., Simulanis, Boundless, and Strivr) now specialize in providing VR training solutions to other organizations, offering tailored programs across a wide range of industries. Because these trainings happen in realistic virtual environments, users can safely practice key tasks and scenarios, as many times as they need. This hands-on approach helps improve user confidence and reduce user error, all at reduced cost (Howard et al., 2021). In much the same way, VRET can be understood as a form of psychological training, where repeated exposure helps users form new, non-threatening associations, consistent with the inhibitory learning model of exposure. Reflecting this growing interest, formal educational programs such as diplomas and certificates in VRET are beginning to emerge (e.g., The Behaviour Institute's Diploma in Virtual Reality Exposure Therapy), aimed at training both clinicians and non-clinicians in the evidence-based practical application of this modality.

Additionally, conversational artificial intelligence (AI) agents and virtual therapists are beginning to play a role in therapy (Spiegel et al., 2024). These systems can guide users through the steps of an exposure session, provide supportive prompts, and debrief users afterward. Some platforms use natural language processing to simulate therapeutic dialogue, enabling a structured but flexible experience even in the absence of a live clinician. While such systems are not intended to replace trained clinicians, they offer a promising way to increase therapeutic reach in areas where professional support is scarce.

While VRET and other virtually-delivered therapies offer new possibilities for scalable, personalized, and immersive treatment, it is also important to acknowledge what may be lost when therapy is delivered in a virtual format. One of the most significant limitations is the absence of in-person, co-regulated emotional presence between therapist and client. In traditional therapy, subtle interpersonal cues, such as body language, tone, and eye contact, play a critical role in establishing safety, empathy, and attunement. These cues are either diminished or absent in most current VR platforms, particularly in self-guided formats or those relying on virtual agents. Even with AI-driven virtual therapists, the therapeutic alliance may not reach the level of nuance or emotional depth possible in human-facilitated sessions. Recognizing these limitations is essential to guide the continued development of virtual therapeutics. Future iterations may benefit from combining virtual exposure with live therapist support or follow-up assignments in the real world to bridge the gap between digital and embodied therapeutic change.

Taken together, these findings suggest that while VRET offers clear benefits in terms of accessibility, scalability, and engagement, its continued development will require careful attention to both the technological and therapeutic design, including the standardization and structure of VRET protocols, which currently remain highly variable. As virtual therapies grow in reach and complexity, the effectiveness of future interventions will increasingly depend on how well they are designed to support psychological principles, therapeutic goals, and user needs. The following sections outline key future directions in two critical areas: the

design of exposure-based therapy itself and the design of the virtual reality technologies that deliver it.

7.2 Limitations of the Present Research

Several overarching limitations of this thesis warrant discussion. First, both case studies employed small, single-arm or non-randomized designs with convenience samples, limiting the strength of causal inferences that can be drawn. The absence of randomization and the use of non-equivalent comparison groups in Chapter 5 mean that observed effects cannot be attributed definitively to the VRET intervention. Second, both case studies used a single-session protocol, which, as discussed in the individual chapter discussions, is unlikely to be sufficient for sustained symptom reduction based on clinical recommendations for OCD and specific phobia treatment. The single-session design was appropriate for early-phase feasibility evaluation but limits conclusions about therapeutic efficacy. Third, the use of commercially developed VR environments whose exposure hierarchies were designed by XRHealth's clinical team, rather than the candidate, limits the degree to which the therapeutic design of the interventions can be fully evaluated or replicated. Fourth, both case studies recruited predominantly young, convenience samples via campus posters and Instagram advertisements, limiting demographic diversity and generalizability. Fifth, follow-up was limited to one month, precluding conclusions about longer-term effects. Sixth, physiological data, though collected in both case studies, were analyzed and reported separately in Chapter 6 rather than being integrated with the intervention outcomes, which limits the ability to draw conclusions about the relationship between physiological and subjective anxiety responses during VRET.

7.3 Future Directions in Design of Exposure-Based Therapy

7.3.1 Personalized Exposure Protocols

One major advantage of VRET is its capacity for customization. Future exposure protocols should take advantage of this by offering exposure hierarchies that are personalized to each individual. For example, an individual with contamination-related OCD may begin with a low-anxiety scene such as touching a door handle in a clean public space, then gradually progress to holding a pole in a busy subway car. Similarly, someone with needle fear could begin with observing a needle in a clinical setting and advance to simulating an injection.

Adaptive algorithms could be implemented to monitor physiological markers such as HR, skin temperature, and EDA in real time, adjusting the exposure intensity accordingly. For instance, if an individual's HR does not rise above a therapeutic threshold and their change in skin temperature was not sufficient, the system could automatically increase the realism or proximity of the feared stimulus. Conversely, if physiological responses indicate overwhelming anxiety, the scenario could be paused or de-escalated to maintain safety and promote learning. The present findings support the feasibility of such personalization, as the psychophysiological data revealed that contamination-related and needle-related

anxiety were associated with distinct physiological profiles. For example, subclinical contamination OCD anxiety showed larger HR and EDA changes, while subclinical needle anxiety was linked to different patterns in skin temperature and HR. These differences suggest that adaptive systems could tailor exposure intensity based on the specific anxiety subtype, enhancing both safety and therapeutic efficacy.

7.3.2 Reinforcing Inhibitory Learning Through Expectancy Violation

Future VRET applications should be designed to optimize inhibitory learning rather than merely promote habituation, to be aligned with the latest in exposure science (Craske et al., 2014). This involves creating scenarios and environments that violate users' expectations in safe, surprising ways. For example, a virtual environment for claustrophobia could simulate riding in a crowded elevator that remains closed for an extended period, during which the user experiences no suffocation, panic escalation, or inability to cope. Similarly, a module targeting dental phobia could simulate sitting in a dentist's chair during a procedure, such as a cleaning or injection, that proceeds calmly and ends without pain, loss of control, or judgment from the practitioner.

To reinforce these learning moments, built-in prompts can be added to help users reflect on their expectations before and after each exposure. Modules might include short reflection screens that ask questions like, "What did you expect would happen?" and "What actually happened?" These reflective prompts help activate key cognitive processes central to CBT and ERP, such as cognitive restructuring and belief updating, which support the translation of exposure experiences into lasting therapeutic change.

7.3.3 Session Structuring and Dosage Optimization

Current exposure-based interventions vary widely in how exposure is administered. Drawing on clinical recommendations (Foa & Kozak, 1986; Foa et al., 2012), particularly in the context of ERP for OCD, sessions should ideally last between 60 and 90 minutes, with 45 to 60 minutes devoted to active exposure. This duration allows anxiety to rise, peak, and begin to decline naturally without safety behaviors or avoidance, a process central to both habituation and inhibitory learning.

In VRET such extended sessions may not always be feasible, due to considerations such as VR sickness or the weight of the HMD, which currently make prolonged VR usage uncomfortable to many individuals. Nonetheless, shorter exposures, ranging from 15 to 30 minutes, can still be effective if conducted with sufficient frequency (Krzystanek et al., 2021). Evidence suggests that more frequent sessions, such as daily or every other day, may lead to faster symptom reduction compared to traditional once-weekly formats, especially during the early stages of intervention (Krzystanek et al., 2021).

A structured procedure can help maintain consistency and therapeutic efficacy across digital formats. Sessions might begin with a brief subjective anxiety rating or mood check-in, followed by an exposure task selected either manually or al-

gorithmically from the individual's personalized hierarchy. The exposure should continue until a meaningful reduction in anxiety is observed, typically defined as at least a 50 percent decrease from the peak anxiety level. This helps prevent premature termination, which can reinforce avoidance rather than promote learning.

After the exposure, users may benefit from guided reflection prompts to consolidate gains and enhance cognitive integration. These could include questions such as what they expected to happen, what actually occurred, and whether their feared outcomes were realized. In a VRET setting, these reflection points could be integrated as part of the session interface. Moreover, physiological data such as HR, skin temperature, and EDA could be used to monitor anxiety levels in real time, allowing the system to adjust the exposure length dynamically or prompt supportive strategies if arousal exceeds a tolerable threshold.

7.3.4 Delivery Models: Clinician-Guided, Self-Guided, and Hybrid

Both therapist-guided and self-guided formats have advantages. One promising direction is to develop hybrid models. A user might begin with a clinician-assisted onboarding session to ensure proper use and safety, followed by self-directed sessions completed at home. Built-in progress tracking, real-time physiological feedback, and secure data sharing with clinicians would allow continued oversight without requiring in-person attendance.

Several flexible configurations are emerging within this hybrid paradigm. One model involves fully self-directed VRET sessions conducted at home potentially after an onboarding session, allowing users to engage with exposure content at their own pace (e.g., Chard et al., 2023; Lacey et al., 2022). Another approach uses VRET as between-session homework, where users complete prescribed exposures independently and the results (e.g., subjective distress ratings and/or physiological data) are reviewed during subsequent in-person or telehealth sessions with a clinician (e.g., Schuler et al., 2025). A related application is using self-guided VRET during the waiting period for therapy, allowing individuals to begin therapeutic engagement even before accessing formal treatment, which may be especially valuable given the widespread backlog in mental health services. VRET can also be deployed specifically for individuals with subclinical symptoms, who may not meet the threshold for formal treatment but could still benefit from low-intensity intervention and structured exposure practice (Boeldt et al., 2019).

Finally, VRET can also be integrated directly into the clinical setting, where therapists remain present and actively guide the exposure in real time. In this model, clinicians can dynamically adjust the scenario, offer in-the-moment coaching, and help process emotional responses immediately afterward. This effectively augments traditional therapy with immersive tools. Together, these models demonstrate the adaptability of VRET to different clinical needs, service structures, and levels of care intensity.

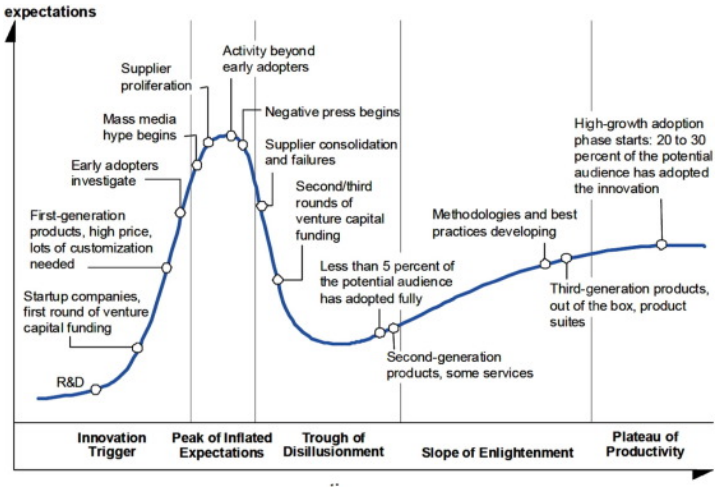
7.3.5 Pre-Design Stakeholder Engagement in Therapy Content

Another important consideration for the future development of exposure-based therapy is the incorporation of human-centered design (HCD) approaches. Existing models, whether delivered in person or through VRET, often rely on theoretical or clinical assumptions that may not fully reflect the lived experiences of those receiving treatment. As therapeutic content, such as exposure scenarios, becomes more personalized, this gap may widen. Involving individuals with direct experience of the targeted symptoms can help ensure that therapeutic materials are more relevant, relatable, and effective. Methods such as participatory design workshops, user interviews, and empathy mapping can be conducted prior to designing VR environments to generate meaningful insights into users' emotional and cognitive needs, while also ensuring early stakeholder involvement and buy-in. These techniques also support the development of exposure scenarios that feel authentic and impactful, rather than artificial or detached from real-life concerns. By involving potential users and clinicians throughout the design process, future exposure-based therapies may become more accessible, acceptable, and aligned with users' values and treatment goals.

7.4 Future Directions in Design of Virtual Reality Technology

The evolution of VR technologies for therapeutic use can be considered through the lens of the Gartner Hype Cycle Figure 7.1, a widely referenced model describing the adoption and visibility trajectory of emerging technologies (Fenn & Raskino, 2008). While the framework has its criticisms (Dedehayir & Steinert, 2016), it remains a useful heuristic for contextualizing the course of development, expectations, and adoption of innovations in digital mental health.

Figure 7.1. The Hype Cycle and Its Stage Indicators



Note. Reprinted from "*The Hype Cycle Model: A Review and Future Directions*," by Ö. Dedehayir and M. Steinert, 2016, *Technological Forecasting and Social Change*, Copyright 2016 by Elsevier. Adapted from an earlier figure in *Mastering the Hype Cycle: How to Choose the Right Innovation at the Right Time*, by J. Fenn and M. Raskino, 2008, Harvard Business Press. Reproduced with permission for academic, non-commercial use.

In the case of VRET, the field appears to be in the early stage of what the Hype Cycle calls the "Slope of Enlightenment." Following initial waves of enthusiasm and some disillusionment regarding technical constraints, variable outcomes, and user side effects such as VR sickness, the technology is now progressing into a phase marked by more cautious optimism, refinement of best practices, and growing integration into real-world contexts. A key aspect of the "Slope of Enlightenment" phase involves discerning the appropriate applications of VR technology. Not all tasks benefit from the immersive qualities of VR. For example, routine activities such as checking emails are not well-suited to VR environments, as their simplicity and frequency are better accommodated by more accessible devices like smartphones or personal computers. In contrast, VR has demonstrated considerable utility in domains such as training, where immersion can enhance experiential learning and skill acquisition (Howard et al., 2021). Exposure-based therapy can also be understood as a form of training, aimed at gradually building psychological resilience through controlled, repeated exposure to feared stimuli. Importantly, VR enables dynamic context shifts within the exposure process by allowing varied scenarios to be presented without requiring physical relocation. This can enhance learning and reduce the likelihood of fear returning in real-world settings (Knowles & Olatunji, 2019; Shiban et al., 2013).

7.4.1 Reducing VR Sickness and Enhancing Realism

VR environments should be designed to minimize user movement and reduce visual-vestibular mismatch, both of which are primary triggers of VR sickness (Stauffert et al., 2020; Tian et al., 2022). Stationary or limited-movement tasks are generally more tolerable than scenarios requiring users to navigate or rotate frequently. These stationary experiences can be delivered while seated, and current VR systems increasingly allow users to align their physical seating (e.g., chair or sofa) with a virtual counterpart, improving comfort, embodiment, and realism.

Strong early cues for embodiment, such as avatar hand syncing, head tracking, and tactile prompts, can also improve immersion and reduce disorientation. These techniques promote the sense that the avatar is an extension of the user's own body, which may improve engagement and therapeutic effectiveness.

Some VR experiences have successfully combined these principles with thoughtful narrative design. For example, in the VR game *Down the Rabbit Hole* ('Down the Rabbit Hole', 2020), movement is deliberately limited to reduce discomfort. The user slowly descends a vertical rabbit hole, minimizing lateral motion and allowing for a sense of progression without disorienting acceleration. Along the descent, users peer into miniature diorama-like scenes embedded in the walls of the 360-degree rabbit hole. This strategy not only minimizes motion but also maintains engagement by inviting exploration in a visually stable and stationary format. When a more immersive or embodied scene is required, the user is seamlessly transported into a full-scale environment, but movement within the scene is kept minimal, typically limited to looking around. This approach demonstrates how narrative coherence and user-centered design (including techniques to reduce VR sickness) can work together to create compelling and comfortable VR experiences. This approach highlights strategies that can be integrated into therapeutic programs, including VRET, to enhance immersion, minimize discomfort, and support sustained engagement during exposure tasks.

7.4.2 Hardware Considerations: Comfort, Accessibility, and Inclusivity

Future hardware should prioritize lightweight and adjustable designs that accommodate different head shapes, hairstyles, glasses, hearing aids, and makeup routines. Many users, particularly those with elaborate or thick hairstyles, makeup, or religious head coverings, may find current VR headsets uncomfortable and disruptive.

Weight and strap fit are significant usability factors. Individuals often report discomfort due to the weight and bulkiness of headsets, and lighter devices can meaningfully extend comfortable wear time (Hornsey & Hibbard, 2024). Headsets should include easy-to-clean or replaceable hygiene liners suitable for contact with makeup or sweat, particularly if one headset is shared with many people. In larger-scale or clinical contexts, specialized sanitation solutions

such as ultraviolet cleaning systems are also being used. For example, companies like Cleanbox provide commercial-grade VR sanitation equipment designed to disinfect headsets between users efficiently, helping to address hygiene concerns in shared or high-turnover environments.

Standalone HMD headsets that are affordable and simple to set up will be key for both clinic and home deployment. Designing VR hardware that is cosmetically considerate, hygienic, and physically comfortable is essential for making VRET inclusive and widely accessible, even as headsets become more affordable and ownership becomes increasingly common.

7.4.3 Real-Time Biofeedback and Adaptive Exposure

Wearable sensors can provide ongoing data about user arousal and engagement, through measures such as HR, EDA, and skin temperature. When combined with adaptive algorithms, these signals can be used to responsively modulate the difficulty of the exposure task. This modulation should keep the user aligned with their individual exposure hierarchy, ensuring that exposure remains within a therapeutic window. If arousal is too low, the system can intensify the scenario to make it more effective. If arousal is too high, the system can pause or reduce intensity to preserve safety and prevent disengagement.

For example, in a VRET scenario targeting fear of flying, the environment might begin with a calm boarding scene and progress to sitting in an airplane. If the user's physiological signals indicate insufficient arousal, the system could escalate the scenario by simulating turbulence or in-flight announcements about delays. Conversely, if the user's arousal spikes beyond a safe threshold, the system could reduce stimuli, such as dimming cabin noise or pausing turbulence, to help the user regain composure while still remaining engaged with the task.

7.4.4 Iterative Human-Centered Design in Virtual Reality Platform Development

In addition to improving technical elements, VR technology, including its applications in therapy, should incorporate HCD and participatory design principles. While *Pre-Design Stakeholder Engagement in Therapy Content* (see Section 7.3.5) focuses on involving stakeholders before the creation of therapeutic content, the activities described here occur after initial therapy content has been developed. At this stage, HCD supports iterative refinement of both the VR platform and the therapeutic scenarios based on user feedback, usability testing, and clinical evaluation. This stage is critical because, at present, it is often unclear how virtual exposure scenarios are created or whether they are informed by individuals with relevant lived or clinical experience.

Many are designed and developed loosely from broad theory or entirely without evidence-based design principles, as is often the case in the development of VR games. A more transparent and collaborative design process would help ensure that the technology meets the needs of both patients and clinicians. HCD typically follows four main activity phases: (1) defining the users and the context in which the technology will be used; (2) determining and prioritizing user requirements; (3) generating design solutions that address these requirements; and (4) evaluating the designs through user feedback to ensure they meet the identified needs (Harte et al., 2017). This structured process supports iterative development and ensures that user perspectives are integrated from early ideation through to implementation.

Including both potential users with targeted symptoms and clinicians in design activities can help align technical development with clinical priorities and individual expectations, making VRET applications both more practical and therapeutically appropriate. In addition, attention to the tone, language, and framing of virtual scenarios is essential, since these factors influence users' sense of psychological safety and their willingness to engage with potentially distressing material. Iterative feedback loops that include usability testing and scenario walkthroughs are critical for identifying and resolving issues that might otherwise disrupt engagement or reduce therapeutic effectiveness. By adopting a user-informed approach grounded in HCD, VRET developers can create more inclusive, trustworthy, and clinically meaningful therapeutic environments.

Alongside HCD approaches, the integration of emerging technologies presents new opportunities to further individualize and optimize virtual therapeutics. AI, in particular, has the

potential to enhance VRET applications by supporting adaptive scenario generation, real-time feedback, and personalized treatment trajectories. However, as AI begins to play a larger role in both backend customization and frontend user interaction, it remains essential to uphold the principles of HCD. Personalization through AI should be guided by user needs, clinical priorities, and ethical considerations to ensure that technological sophistication does not come at the expense of user trust, safety, or relevance.

7.4.5 AI Integration: Customization, Guidance, and Virtual Therapists

AI will play a growing role in both backend customization and frontend user interaction within VRET systems. On the backend, AI can help generate individualized exposure scenarios by analyzing symptom profiles, session history, physiological responses, and user feedback. For instance, a user with contamination-related OCD who demonstrates high arousal in a public restroom scenario might be assigned to repeat that environment with gradual increases in difficulty, such as more visible grime or a lack of cleaning options.

To support wider implementation, particularly in non-specialist and community settings, it is essential that future VRET platforms be designed with usability in mind for clinicians who do not have technical or programming expertise. Currently, many VR applications require adjustments to be made at the code level or through developer interfaces, which limits their practical utility in routine care. Generative AI offers a promising solution to this challenge. By allowing clinicians to describe desired exposure scenarios in natural language, such as "a moderately crowded subway car during rush hour," the system could automatically generate a corresponding virtual environment. It could adjust variables like crowd density, ambient noise, or the user's distance from others based on the clinician's input. This kind of intuitive, language-based interface would allow clinicians to personalize exposure content such as intensity, pacing, and context without needing to write code or navigate complex technical settings. Making these tools more accessible to clinicians is crucial for integrating VRET into therapeutic practice across a wide range of settings.

On the front end, AI-driven virtual therapists can provide real-time guidance. These agents may introduce the task, suggest coping strategies, and debrief users after the exposure. For example, if a user hesitates before starting an exposure, the virtual therapist could detect elevated arousal, respond with a motivational prompt, and offer to adjust the difficulty. As natural language processing improves, these agents may become more emotionally responsive, fine-tuned to the individual user, and better at maintaining therapeutic engagement.

7.4.6 Affordability, Equity of Access, and Implementation within Healthcare Systems

To achieve the promise of democratized mental health care, VRET must remain affordable and widely accessible. Collaborations with public health systems and device manufacturers could enable subsidized access for at-risk groups, while clinical settings could offer shared devices for use in community health centers, schools, or mobile clinics. These approaches can reduce financial barriers and support outreach in underserved areas.

In the UK, the National Health Service (NHS) has begun integrating VR-based psychological therapies into routine care. For example, a VR treatment for severe agoraphobia, funded by the National Institute for Health and Care Research (NIHR), has been approved for implementation following endorsement by National Institute for Health and Care Excellence (NICE) ('NIHR-funded Virtual Reality treatment recommended for use in NHS | NIHR', 2025; *Virtual Reality Exposure Therapy for Subclinical Obsessive Compulsive Disorder*, 2023). In the US, the regulatory landscape has evolved to support similar innovations and the first VR therapeutics have received Food and Drug Administration (FDA) authorization, which allows for future insurance reimbursement. One prominent example is AppliedVR's (formerly RelieVRx) EaseVRx platform, which received FDA market authorization for chronic lower-back pain and was assigned a durable medical equipment billing code by the Centers for Medicare & Medicaid Services (CMS), enabling Medicare reimbursement (Maddox et al., 2025). To date, the FDA has approved 69 augmented reality (AR) and VR applications, classified as authorized medical

devices ('Augmented Reality and Virtual Reality in Medical Devices', 2025). However, none of these are based in VRET. As more VR treatments obtain regulatory approval, similar pathways could allow for national health service prescribing or private insurance reimbursement, lowering financial barriers for patients and expanding access on a larger scale.

Scalability depends not only on affordability and regulatory approval, but also on careful integration into established clinical workflows. Incorporating VRET into existing stepped-care programs, such as NHS Talking Therapies, could enable therapists to assign VR exposure sessions as structured homework between in-person visits. This would reduce clinician time demands while maintaining therapeutic continuity. Platforms like XRHealth already offer models for such delivery, supporting both clinician-led and self-guided sessions in structured digital environments. These models illustrate the potential for VRET to complement and enhance standard care delivery without requiring a fundamental restructuring of mental health services.

Despite these advancements, digital inclusion remains a critical concern. Although consumer-grade headsets such as the Meta Quest 2 are more affordable than earlier technologies, they may still pose a barrier for individuals with limited financial resources, inadequate digital literacy, or restricted access to reliable internet and private physical space for VR use. These factors could exacerbate existing disparities in mental health service access, particularly among older adults, individuals with disabilities, and residents of rural or socioeconomically disadvantaged areas.

To ensure equitable implementation, VRET programs must be designed with these challenges in mind. Community-based headset lending schemes, integration of virtual exposure tools into low-cost or mobile-accessible applications, and introductory support for new users are all viable strategies to reduce exclusion. In parallel, participatory design processes should involve digitally underserved populations in the development of content and delivery formats to ensure relevance and accessibility. Moreover, future research should adopt implementation science frameworks to study how VRET can be safely, ethically, and effectively introduced into diverse real-world contexts, including public health systems, education settings, and remote healthcare delivery channels.

Taken together, affordability, clinical integration, and digital inclusivity must be addressed simultaneously for VRET to fulfill its potential as a scalable and equitable intervention. These considerations are especially pressing in light of the growing interest in digital mental health tools as a means of expanding reach and addressing gaps in traditional service provision.

7.4.7 Concluding Remarks

This PhD project demonstrates that VRET is a feasible and well-tolerated intervention for individuals experiencing subclinical anxiety. The studies presented show that commercially available VR environments can reliably evoke targeted anxiety responses and are perceived by users as engaging and acceptable. While the interventions did not yield significant symptom reduction within the study period, the findings support the potential of VRET as a platform for delivering exposure-based therapy in innovative and accessible ways. This work contributes to a growing evidence base on digital mental health interventions and highlights important design and implementation considerations for future research. As psychological services increasingly look toward scalable solutions, this thesis offers a step toward understanding how immersive technology can support mental health care beyond traditional methods. It lays a foundation for future studies to refine, extend, and implement VRET in real-world contexts.

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A | Appendix: Case Study I: VRET for OCD

Table A.1. Correlations Between Main Study Variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Perceived OCD symptoms 1													
2. Perceived OCD symptoms 2	.40												
3. Perceived OCD symptoms 3	.30	.39											
4. Baseline contamination symptoms	.19	.34	.12										
5. Average anxiety in exposure 1 (SUDS)	.53	.34	.40	.06									
6. Average anxiety in exposure 2 (SUDS)	.43	.15	.36	-.04	.91***								
7. Baseline positive affect	-.25	-.14	-.48	.03	-.23	-.21							
8. Baseline negative affect	-.08	.03	.04	.57	.32	.36	.17						
9. VR sickness after exposure 1	.18	.25	.18	.01	.41	.23	-.43	.10					
10. VR sickness after exposure 2	.56	.50	.34	.47	.52	.36	-.09	.18	.45				
11. System usability scale	.01	-.19	-.12	.17	-.03	.16	.21	.07	-.66	-.29			
12. Post-intervention contamination symptoms	.20	.04	.26	.46	-.07	-.03	-.11	.07	-.37	.17	.32		
13. Post-intervention positive affect	.05	-.36	-.21	-.17	-.16	-.10	.34	-.19	-.06	-.09	.15	.00	
14. Post-intervention negative affect	.06	.01	.37	.13	.60	.68	-.12	.61	.09	.21	.07	.28	-.21

Note. Post-imputation pooled Spearman's ρ shown with False Discovery Rate correction applied.
*$p < .05$. **$p < .01$. ***$p < .001$.

Table A.2. Frequencies of Item Endorsement on the System Usability Scale

	1 strongly disagree *n*(%)	2 *n*(%)	3 *n*(%)	4 *n*(%)	5 strongly agree *n*(%)	M (SD)
I think that I would like to use this system frequently.	4 (25.00)	2 (12.50)	6 (37.50)	3 (18.75)	1 (6.25)	2.69 (1.21)
I found the system unnecessarily complex.	8 (0.50)	6 (37.50)	1 (6.25)	0	1 (6.25)	1.75 (1.03)
I thought the system was easy to use.	1 (6.25)	0	2 (12.50)	7 (43.75)	6 (37.50)	4.06 (1.03)
I think that I would need the support of a technical person to be able to use this system.	8 (50.00)	2 (12.50)	3 (18.75)	2 (12.50)	1 (6.25)	2.13 (1.32)
I found the various functions in this system were well integrated.	2 (13.33)	1 (6.67)	4 (26.67)	7 (46.67)	1 (6.67)	3.27 (1.12)
I thought there was too much inconsistency in this system.	3 (18.75)	10 (62.50)	2 (12.50)	1 (6.25)	0	2.06 (0.75)
I would imagine that most people would learn to use this system very quickly.	1 (6.25)	0	2 (12.50)	9 (56.25)	4 (25.00)	3.94 (0.97)
I found the system very cumbersome to use.	4 (25.00)	7 (43.75)	4 (25.00)	1 (6.25)	0	2.07 (0.85)
I felt very confident using the system.	0	2 (12.50)	3 (18.75)	7 (43.75)	4 (25.00)	3.81 (0.95)
I needed to learn a lot of things before I could get going with this system.	9 (56.25)	3 (18.75)	2 (12.50)	1 (6.25)	1 (6.25)	1.88 (1.22)

Note. This table represents data pre-imputation.

Table A.3. Feedback and Acceptability Open-Ended Responses

Question	Participant Response
How did you feel while you were taking part in the virtual reality experience?	Intrigued about what would happen next, yet also anxious.
	The initial 'unknown' experience made me feel uncomfortable, however knowing what was coming, in the second environment, made me feel more anxious, where I thought that it would make me feel less anxious, as I knew what I would be faced with.
	Intrigued about what would happen next, yet also anxious.
	uncomfortable, disgusted
	I felt disgusted by the surroundings, especially the cubicle
	Excited at first and then a little nervous as we put the headset on.
	Overall quite uncomfortable
	I felt quite unprepared and awkward because I didn't know what to expect and I couldn't see what my reactions were like. I also felt quite determined to get through it even it seemed daunting.
	I felt nervous, then I felt gross when I got in the bathroom
	anxious due to unfamiliarity and unease around public toilets, slightly overwhelmed and at first dizzy/uncoordinated
	I feel it is really realistic and it makes me feel surreal
	interested and curious
	normal, then grossed out and with a slight eye strain
	curious but not too worried
	I felt nervous about the study itself and trying to figure out what I was supposed to be feeling. I did also feel grossed out by the environment, but it didn't feel real enough to make me feel like I was actually there. But it was still a bit oppressive, and together with the motion sickness of the VR headset, I did feel quite uncomfortable.
	Quite interesting in general, this is the first time I used a VR set.
What did you think when you saw the contaminated environment?	It reminded me of previous experiences I have had in this scenario.
	it was not safe
	I was wondering as to how an environment could reach that point - and reminded me of an experience that I have had recently, where I was in a similar situation - and upon reflection, I can now see myself doing things in my real-life environment that I didn't notice at the time, however I avoided them/did them differently, at the time.
	I thought it was disgusting and wanted to leave as soon as possible

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Table A.3 – *Continued from previous page*

Question	**Participant Response**
	That it was very dirty and I'd need to not touch anything.
	It was very realistic, I didn't want to open the cubicle door (details like loo roll on the floor and the gross full bin made it more realistic)
	I was quite surprised about the realness of it in general because it matched the kind of environment I had pictured better than I thought it would. I also thought that it was really unpleasant in general.
	that i wanted to leave straight away, i would've rather gone to pee outside somewhere in a park
	I thought it was a particularly disgusting bathroom. I would have immediately left if I wasn't absolutely desperate. I noticed the trash on the floor and grimy toilet seat the most. I also noticed the Pepe on the door and thought that was fun.
	that I wouldn't want to be there
	I feel I want to finish everything really quick without touching anything and leave
	I want to escape
	disgust
	It looked typical based on the outside environment
	It's normal in public place
	I didn't like it, I could imagine one in real life
How did you feel when you saw the contaminated environment?	It made me feel anxious, reluctant to use, on edge.
	slightly nervous
	The initial 'unknown' experience made me feel uncomfortable, however knowing what was coming, in the second environment, made me feel more anxious, where I thought that it would make me feel less anxious, as I knew what I would be faced with.
	I felt disappointed but not surprised
	I felt nervous and contaminated
	I felt sweaty and dirty.
	tense
	Slightly anxious and ill at ease
	Feeling rushed to complete the stuff as soon as possible
	I felt disgusted and repulsed, and quite uncomfortable. I just really wanted to leave.
	I felt gross and dirty

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Table A.3 – *Continued from previous page*

Question	**Participant Response**
	that I wouldn't want to be there
	anxious and distressed, not wanting to touch anything
	I didn't feel distressed but I felt a bit uneasy. I also felt quite unsafe and exposed.
	At first a little disgust, especially when wiping the toilet clean is not an option, but otherwise it is alright.
	I feel quite a bit stressed and upset.
In your opinion, is there anything that could have been done differently to improve the software or create a better experience (in any aspect)?	Adding smell and sound as these could alter the experience significantly
	Adding the smell to make it more realistic. Make participants sit on a real toilet.
	smell or touch elements
	Different headset that can change the focus for people with glasses - could have taken off my glasses, and still been able to see.
	High resolution, higher framerate, more comfortable headset to wear
	Maybe having real objects to touch when going through the motions of the simulation
	More freedom in choosing what to do.
	I would maybe improve the visual environment's quality
	Smell should be simulated simultaneously when running the VR application; The VR scene is not that horrible enough.
	Some of the graphics were a little blurry and the avatar's body blocked the view of some elements so perhaps adjusting the dimensions of the avatar could enhance the viewing experience.
	Somehow trying to recreate the smell, though that might be quite gross. Also, in the cubicle scene, the view of the actual toilet, where the water is, was blocked by the avatars body and I couldn't maneuver past it in any way. I think I could see the bowl better, and if it was perhaps blocked and smeared with poop, and the floor was wet, I would've felt much more distressed. Also maybe if the environment had been changing more, like someone banging on the door or sounds of other people defecating, it would've felt more real. I think those are the kind of experiences that the VR might actually make me more resilient too.
	The body can be smaller, giving a better field of view. Maybe adding the actual walking animations instead of teleporting around.
	The flesh was luminous and the body obscured a lot of things (e.g. toilet brush).

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Table A.3 – *Continued from previous page*

Question	**Participant Response**
	calibrate the avatar better so it won't block the scenario
	maybe more realism, such as feeling a wall or acting it out, maybe smelling the environment
	smaller avatar body so the field of vision wasn't blocked
Do you have any additional comments about the virtual reality program and/or your experience with it?	It was an enjoyable, fun experience and a good way for exposure therapy without causing too much distress.
	Difficult to do so with glasses, however once that issue had been sorted, the overall environment was 'enjoyable'
	The environment wasn't very detailed.
	It would be interesting to do different scenarios, such as using a urinal rather than a stall. Also experimenting with space and manipulating other senses, such as smell and sound
	I felt uncomfortable performing the actions the avatar was performing (i.e. acting them out in the real world whilst wearing VR) but maybe that could have made it more realistic.
	Adding in smell or touch elements to the VR experience could help you feel more immersed, but overall it was very good and well instructed. I can see how multiple sessions of this kind could help with this issue as it wouldn't feel so daunting to enter contaminated places of this kind.
	Generally interesting
	I thought it was pretty exciting realistic looking, would be much more interactive if I was able to perform the actual tasks the avatar did automatically such as touch the wall or sit down without a change in the perspective.
	it was interesting since it was my first time using VR
	I feel like the lack of actually moving and feeling things like the toilet brush or toilet seat took me out of the experience of actually being there
	if it was more realistic it would have felt more immersive but also cause more anxiety so i think it was done well
	I think it is good in general.
	The scene was not very delicate and detailed but it was really realistic
	VR is really interesting. It was a nice experience.
	was great
	I wonder if there was less of a virtual barrier, (meaning if I actually felt as if it was a real toilet) if my anxiety and concerns would feel more real

B Appendix: Case Study II: VRET for Fear of Needles

Table B.1. Shapiro-Wilk Test Results for Main Study Variables

Experimental Group		
Variable	**W**	**p-value**
MFS Initial Score	0.97	0.545
SPQ Initial Severity Score	0.95	0.198
SPQ Initial Interference Score	0.91	0.011*
Anxiety Pre-Images	0.83	< .001***
Anxiety Post-Images	0.92	0.016*
Anxiety Follow-Up Pre-Image	0.95	0.116
Anxiety Follow-Up Post-Image	0.93	0.035*
Positive Affect at baseline	0.98	0.859
Negative Affect at baseline	0.91	0.011*
Positive Affect at end of intervention	0.88	0.002**
Negative Affect at end of intervention	0.86	0.001**
SPQ Follow-Up Severity Score	0.98	0.799
SPQ Follow-Up Interference Score	0.91	0.015*
MFS Follow-Up Score	0.95	0.199
Comparison Group		
Variable	**W**	**p-value**
MFS Initial Score	0.85	< .001***
SPQ Initial Severity Score	0.91	0.011*
SPQ Initial Interference Score	0.85	< .001***
Anxiety Pre-Image	0.86	0.001***
Anxiety Post-Image	0.86	0.001***
Positive Affect at baseline	0.96	0.242
Negative Affect at baseline	0.72	< .001***
Positive Affect at end of intervention	0.96	0.282
Negative Affect at end of intervention	0.74	< .001***

Note. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table B.2. Selection of Feedback and Acceptability Open-Ended Responses

Question	Participant Response
How did you feel while you were taking part in the virtual reality experience?	A bit nervous as the VR is quite real, I would say the second time is better as I'm more used to the environment and know what is exactly going to happen.
	The VR experience felt somewhat real, as there was the actual sensation of having an injection/blood taken, albeit on a lesser scale. The thought of actually having blood taken did make me feel quite anxious, however knowing that it wasn't actually happening made me feel somewhat calmer.
	the experience was really interesting. Although the graphics made it clear that it was a simulated environment, certain elements made it feel very real. I felt similarly to how I feel when I am getting an injection.
	I felt interested at first, curious and then a bit more nervous as it looked quite realistic.
	I felt almost exactly as if I were having a real injection/blood test. My palms became quite sweaty and I could feel my heart in my chest. I also felt slightly light headed. It was very realistic, especially being touched at the time the needle goes in.
	Anxious, but more comfortable than in reality. I think it was close enough to reality that I felt anxious, but distant enough that I didn't totally panic.
	I was comfortable overall but felt that the VR scene was quite realistic. I imagined that I was in the same situation and think that my response to the VR and to a real-life scenario would be similar.
	The VR looks almost real. I almost felt like I was in a hospital attending to a nurse.
	The virtual reality was a good insight into replicating the feelings felt when receiving an injection, it reminded me of the same feelings I felt when getting a real injection.
	it was really fun experience and the interaction were pleasant
	Stress of being in an environment that was related to pain.
	overall I was more nervous than I thought, I think the multiple shots actually induced a fear of needles but by the second time it was slightly less scary as I'd done it so many times. the VR itself was quite motion sickness inducing, when he walked towards the clinic.
	The experience felt very real in terms of sensations than visuals. When the blood drawing simulations ended, I felt slight pain in the area of my arm where tactile sensations were presented.
	At first, I found the procedures very unexpected and definitely wasn't expecting the experimenter to actually touch my arm to make me feel like I was getting an actual injection. After watching the video and knowing that the same procedure is going to be repeated, I was less anxious.
	felt as if i was really in the clinic and was excited but intrigued.
	It was interesting, the graphics were a little unusual and confusing but it felt fine.
What did you think when you saw the medical environment?	I don't like that, especially the blood samples on the right.
	It felt quite realistic. People seemed serious.
	Curious and uncomfortable but mainly thinking about what might happen/didn't feel very present.
	As I have diabetes, seeing the medical environment didn't phase me much, as this is something that I am quite used to, now.
	Once I knew I was there for an injection I was less willing to be there. Quite realistic, though there weren't the smells I tend to associate with a medical environment.

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Table B.2 – *Continued from previous page*

Question	**Participant Response**
	It made me feel a bit apprehensive and reminded me of unpleasant situations I have had in hospitals or while visiting my doctor.
	It looked too dissimilar from real life for me to be immersed and actually believe I was in the real situation.
	It looked realistic and I did have the sensation of waiting in a waiting room. Of course the graphics aren't photo real but it still felt as if I was there.
	Slightly nervous but not very anxious because I did not see silver, medical instruments
	Nervous, it looked like a stereotypical medical office with posters about vaccination which always make you anxious anyway!
	Didn't feel like it was very realistic - the fact that it was animated figures definitely made it less nerve wracking that it would normally be for me.
	I thought it was somewhat realistic.
	I felt that it was realistic and showed waiting in a clinic quite well. It put me in the scene and allowed me to imagine that I was really there.
	Felt like other medical environments I've been in, just more unfamiliar.
	The setting and environment was very realistic down to the sounds when waiting and how when entering the room to get the injection it is silent and awkward waiting for the injection.
	Felt like I was there for real, especially with the sound coming from different directions.
How did you feel when you saw the needle?	I feel extremely nervous when I saw that, feeling it's going to be injected my skin soon.
	Fear/wanting to pull back, It felt quite 'real', and even more 'real' if I was looking at the needle while it was in.
	I tried to look away when I knew that the needle was 'on show', so that I didn't make myself feel more anxious, from looking at it.
	I tried not to look at the needle. But on the second round I look at it during the longer draw and had to immediately look away.
	Nervous. My hands were sweatier. Less nervous than I would be in reality - I normally can't even look at one going into me.
	It reminded me of a few accidents that I have had while a nurse has tried to take my blood from my vein. There was one time when she took 4 tries before managing it and I remembered it and I felt extremely uneasy.
	I felt anxious and nervous when I saw the needle. During the first session I turned my head away (as I would in real life) but in the second session I forced myself to look at it and it did help seeing the progress of the blood test.
	Irrational, afraid and anxious however I can look at a needle and observe it for a few moments I cannot however, fathom seeing the needle inserted in to my arm.
	First time - scared. After that, not as scared.
	I felt neutral just seeing the needle, rather it was the needle entering my avatar's arm that caused me discomfort. I did not like seeing the needle in the avatar's arm and felt squeamish when I looked at it.
	I felt scared . It reminded me of last time I had to take an injection for vaccine.
	Anxious, nervous and definitely an increased heart rate.
	Anxious, but watching it come near helps.
	not as anxious as I would in real life, when I felt the sensation in real life that was when I actually became nervous.
	I tried to look at the needle in the second part of the experiment, and it still made me uncomfortable. I never look at needles piercing through the skin, so that was a big step for me.
	Anxious, but kind of fun after the first one.

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Table B.2 – *Continued from previous page*

Question	**Participant Response**
In your opinion, is there anything that could have been done differently to improve the software or create a better experience (in any aspect)?	Pinch the skin for the sensation to feel more realistic. The nurse could have been a lot more friendly and less serious. The movement/design of the VR could be more realistic, to help keep more similarities between the VR environment, and 'real life'. The graphics were the primary thing that made it difficult to fully engage/become immersed in the experience. Perhaps changing the dialogue a little bit in the second round, and some more context behind the injections. To make it more realistic- maybe more sounds that you'd normally hear in a hospital (less focused on conversations between people). The eye level of the avatar could possibly be altered to each subject. I could not immerse myself in the simulation especially because I did not feel like I was the avatar getting the injection. Just the bit where you walk into the doctor's office was strange as I was sitting down but my VR self was walking so it made me a bit motion sick. If the graphics of the people could improve that would help too. But in general I thought it was very good. I'm not sure- maybe something to do with some background about why I needed the injection/blood draw etc. maybe it would increase the feeling of obligation which would usually motivate me getting an injection. Maybe consider adding headphones to the set up to enhance the hearing effects. Maybe have real life people in the VR instead of 3D characters. Making me stand up and walk around when my avatar was told to, and telling me to extend my arm to do the tests when my avatar did. To improve (this would be hard) but replicating the pain when getting the needle injected would make the setting be more realistic, though requiring consent, anything pointy and putting more pressure would make it more realistic. More happening around me as it would be in a real clinic. The human models could move their lips as they speak and the models could be more rendered, making them more realistic. The characters and door closing need to be more realistic. The color gradient wasn't quite accurate and the clothing particularly as the characters moved it looked rather unnatural.
Do you have any additional comments about the virtual reality program and/or your experience with it?	It was an enjoyable, fun experience and a good way for exposure therapy without causing too much distress. I think the VR is quite real, it has both images, sounds conversations to make it more realistic. Perhaps can simulate the hospital smell too. It was very fun and interesting, sitting in the clinic waiting area felt real but going inside the room for injection not so much. I think its a really good idea and helps rehearse the scenario beforehand so it feels a lot less anxiety inducing. It felt quite real. It was quite odd, and I wasn't expecting it to be as life like as it was even though it was animated. The movement of the people in the environment was not 'true to life', and therefore reminded me that this was a virtual experience, and the fact that the experience was more cartoon-y made me remember that this wasn't real. I think that the program is a good idea, and if developed more, could have applications beyond simply study. I think that injections are a good application for this. it was quite realistic in simulating the scenario but not so much at the same time. i could remind myself it wasn't real, but it was very comfortable to use and look around with.

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Table B.2 – *Continued from previous page*

Question	**Participant Response**
	It was a very interesting experience and I think it simulates a real environment quite well.
	I think the virtual program could use real people instead of cartoon characters to help individuals truly get immersed in the simulation.
	I actually think that if I did this periodically over a few months and especially right before an injection, it could help my phobia. I think my fear is heightened because I don't often have injections, so my anxiety is higher when I have them because I am not used to them. Whereas this experience could help me get used to the process and seeing needles, which would hopefully make me calmer in that situation in real life. If there are needles on tv/in films I always look away but this has made me think my phobia could improve if I expose myself to them more as I they will become more normal.
	The character models and movements can be improved with motion capture technology for more realistic display.
	Using VR is really good to immerse people in a desired environment, replicating the sounds and settings even up to the skin color of the person.
	More immersion in acting out what was asked, like squeezing your hands, putting your arm out etc may have helped remove disassociation.
	It was more realistic than I'd expected, but please change the part where he walks, it made me quite nauseous. everything else was great and really simulated the anxiety of getting a shot at the GP.
	I think it really helped with needle nerves but I noticed some of the people in the waiting room their eyes weren't animated properly , kind of skinwalker eyes. was uncanny/eerie.

C Appendix: Wearable Detection of Divergent Anxiety Types

Table C.1. 5-Fold Cross-Validation Results for Contamination Anxiety Experiment 1

Model	Accuracy % (SD)	F1 Score (SD)
SVM	90.51 (0.11)	0.88 (0)
KNN	99.08 (0.05)	0.99 (0)
Decision Tree	71.15 (0.63)	0.63 (0)
Random Forest	67.10 (0.15)	0.40 (0)

Table C.2. 5-Fold Cross-Validation Results for Contamination Anxiety Experiment 2

Model	Accuracy % (SD)	F1 Score (SD)
SVM	98.02 (0.07)	0.97 (0)
KNN	99.67 (0.10)	0.99 (0)
Decision Tree	85.14 (0.40)	0.76 (0.01)
Random Forest	68.75 (0)	0 (0)

Table C.3. 5-Fold Cross-Validation Results for Needle Anxiety Experiment 1

Model	Accuracy % (SD)	F1 Score (SD)
SVM	83.36 (0.14)	0.83 (0)
KNN	99.16 (0.04)	0.99 (0)
Decision Tree	64.51 (0.62)	0.58 (0.02)
Random Forest	62.16 (0.22)	0.59 (0)

27 February 2025

To XRHealth,

I am completing my PhD thesis at Imperial College London entitled *Investigating the Feasibility & Design of Virtual Reality Exposure Therapy for Subclinical Anxiety*.

I am writing to request your permission to include screenshots of the subway bathroom and waiting room blood test virtual reality environments from the VR software in my thesis and in related peer-reviewed publications.

My thesis will be added to Spiral, Imperial's institutional repository http://spiral.imperial.ac.uk/ and made available to the public under a Creative Commons Attributions-Non Commercial 4.0 International License (CC BY-NC).

If you are willing to grant me all the permissions requested, kindly return a signed copy of this letter. Alternatively, if you wish to grant only a subset of the permissions, please specify which ones and then sign.

Sincerely,

Anna Caltabiano

Permission granted for the use requested above:

I confirm that I am the copyright holder of the virtual reality software above and hereby give permission to include screenshot images of it in your thesis and resulting peer-reviewed publications which will be made available, via the internet, for non-commercial purposes under the terms of the user licence.

Signed:

Name: Júlia Cárdenas

Organisation: XRHealth

Job title: Account Manager and Psychologist

Table C.4. 5-Fold Cross-Validation Results for Needle Anxiety Experiment 2

Model	**Accuracy % (SD)**	**F1 Score (SD)**
SVM	95.71 (0.21)	0.97 (0)
KNN	99.26 (0.12)	0.99 (0)
Decision Tree	74.32 (0.33)	0.84 (0)
Random Forest	68.75 (0)	0.81 (0)