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REVIEW

Virtual Reality-Enhanced Extinction of Phobias and Post-Traumatic Stress

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Abstract Virtual reality (VR) refers to an advanced technological communication interface in which the user is actively participating in a computer-generated 3-dimensional virtual world that includes computer sensory input devices used to simulate real-world interactive experiences. VR has been used within psychiatric treatment for anxiety disorders, particularly specific phobias and post-traumatic stress disorder, given several advantages that VR provides for use within treatment for these disorders. Exposure therapy for anxiety disorder is grounded in fear-conditioning models, in which extinction learning involves the process through which conditioned fear responses decrease or are inhibited. The present review will provide an overview of extinction training and anxiety disorder treatment, advantages for using VR within extinction training, a review of the literature regarding the effectiveness of VR within exposure therapy for specific phobias and post-traumatic stress disorder, and limitations and future directions of the extant empirical literature.

Keywords Extinction training · exposure therapy · technology · specific phobias · PTSD · psychiatric treatment

Introduction

Virtual reality (VR), a term first coined by Jaron Lamier in 1986, refers to an advanced technological communication interface in which the user is actively participating in a computer generated 3-dimensional (3D) virtual world that includes computer sensory input devices used to simulate real-world interactive experiences [1–3]. Users are outfitted with a head-mounted display composed of separate displays screens for each eye along with a head-tracking device. This allows the user's orientation in the virtual world to change naturally based on head and body movements, which provides users with a sense of presence and immersion within the virtual environment. Users often wear headphones for auditory stimuli [4], and in some environments users may have a sensory pointing device or joystick to interact with the virtual environment [1, 5].

VR applications have been developed for use within psychiatric treatment for many different disorders. The bulk of the VR applications within psychiatric treatment have been for anxiety disorders, particularly specific phobias and post-traumatic stress disorder (PTSD), given several advantages that VR provides for use within treatment for these disorders. The focus of the current article is to provide an overview of extinction training and anxiety disorder treatment, present the advantages provided by VR applications within extinction learning and anxiety disorder treatment, and review the extant literature regarding the effectiveness of VR approaches to the treatment of specific phobias and PTSD.

Extinction Training and Anxiety Disorder Treatment

Anxiety disorders, characterized by pathological fear and anxiety, account for 14.6% of disability-adjusted life years globally, indicating that these disorders have a significant disease burden [6]. Pavlovian fear-conditioning models have been used to understand, behaviorally and neurobiologically, how

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fear responses are acquired (i.e., fear acquisition) and inhibited (i.e., fear extinction) [7]. Within this paradigm, a neutral stimulus, or conditioned stimulus (CS), is repeatedly paired with an innately aversive unconditioned stimulus (US), causing the subject to demonstrate conditioned fear responses to the previously neutral CS. Fear-extinction training is the process through which conditioned fear responses decrease or are inhibited. In this process, the patient is presented with the CS without the presence of the US and after multiple presentations will demonstrate a decrease in the conditioned fear response, known as "extinction learning" [8]. This process has strong clinical relevance as it provides a foundation for how to understand and treat excessive fear and anxiety.

Extinction learning provides the basis for exposure therapy, in which patients confront feared stimuli in a systematic, gradual, and therapeutic manner. The empirical literature provides strong support for the effectiveness of exposure therapy for anxiety disorders [9]. Based on emotional processing theory [10], fear responses are conceptualized as pathological when the associations among stimuli, responses, and meaning propositions, referred to as the "fear network", are inaccurate such that neutral stimuli or responses are associated with an exaggerated probability of threat or danger. Consistent with extinction learning, exposure therapy involves activating the fear network via exposure to feared stimuli, resulting in the patient learning that their feared outcome will not occur and that their conditioned fear response will decrease. In traditional exposure therapy, treatment may involve *in vivo* exposures, in which the patient confronts the feared stimuli in real life, or imaginal exposure, in which the feared stimuli is confronted in the patient's imagination during the therapy session. VR was proposed as a new medium for presenting the feared stimuli approximately 2 decades ago [11].

Advantages of Using VR for Extinction Training

Foa and Kozak [10] propose multiple variables as crucial for optimal activation of the fear network during exposure therapy, including: 1) the information presented during therapeutic exposures must demonstrate strong match with the patient's feared stimuli; and 2) the patient must attend to and engage with the information. Effective activation of fear is essential to extinction learning, as the fear response is only expected to decrease when feared stimuli is repeatedly presented in the absence of aversive consequences. VR technology provides several potential advantages for the process of extinction learning during exposure therapy. Consistent with Foa and Kozak's [10] highlighted variables, VR provides the opportunity to maximize the fit between the exposure and the patient's feared stimuli. First, VR technology provides the opportunity to include aspects of feared stimuli that could otherwise be too expensive or impractical. For instance, multiple virtual flights can be implemented, which could be prohibitively costly, and labor- and time-intensive if attempted *in vivo*. Additionally, VR provides the ability for the therapist to have total control over all aspects of the exposure. For example, a therapist conducting an exposure for flight phobia can assess the patient's specific fears in detail prior to the VR exposures (VREs) and tailor aspects of the exposure, such as the weather on the flight, the amount of turbulence, or the time of day, to maximize the match. This level of control also allows for repetition of aspects of the exposure which may not be possible in real life, such as repeating the take-off several times within session. VRE provides a safe and controlled environment for the patients in which they are able to engage with specific feared stimuli under the direction of a provider, in order to most effectively and efficiently generate changes in conditioned fear responses and maladaptive patterns of thoughts and feelings. Additionally, patient acceptability may be higher than other types of exposure for some patients.

VRE may help patients more effectively attend during exposures. First, through the 3D visuals and position sensors that dynamically move with the patient's natural head movement, VR can provide a high level of presence and immersion within the exposure, which may allow for higher engagement and fewer distractions than other methods. VR provides the ability to engage multiple senses during the exposure, through tailoring the visual and auditory stimuli in the virtual environment, engaging the patient's sense of touch and vibration (by modifying vibrotactile platforms), and the adding relevant smells. This dynamic interaction between the patient and the virtual environment and the ability to engage multiple senses facilitates a sense of truly "being there". Indeed, a previous study found that adding additional types of sensory input within VR, such as olfactory and auditory cues, increased participant's sense of presence and memory of the virtual environment [12]. These higher levels of presence may result in increased attention to feared stimuli and lower levels of cognitive avoidance, which would facilitate effective extinction learning. In particular, VRE may remove barriers to exposure treatment for patients who might struggle with traditional imaginal exposure due to difficulties with visualization or imagination. Additionally, the privacy of the VRE, as opposed to *in vivo* exposures conducted in public, may allow some patients to engage more openly without concern of embarrassment or violation of confidentiality. VR provides the advantage of allowing exposures to be conducted in multiple different contexts with relative ease. As there is evidence that extinction training is context-specific, and therefore fear is more likely to return in contexts other than the one in which extinction training occurred, VR exposure across multiple contexts may increase generalization and decrease the risk of fear renewal.

The sense of presence elicited by VR and the ability to tailor the virtual environment to specific feared stimuli makes VR technology ideal for use within exposure therapy for anxiety disorders. Within fear-based disorders, extinction and learning and VRE are particularly well suited to PTSD and specific phobias. PTSD could be thought of as the quintessential learned fear disorder, as experiencing a traumatic event (US) can lead to excessive fear responses to previously neutral cues (CS) that are associated with the traumatic event, and the traumatic event can be conceptualized as the conditioning episode. For specific phobia, the nature of excessive fear related to a specific object provides a strong opportunity to conduct extinction training by implementing repeated exposures to the specific feared stimuli. As such, the present review will focus on empirical literature surrounding VRE for specific phobias and PTSD. Regarding the scope of the present review, our main focus was efficacy studies, including open trials and randomized controlled trials (RCTs), investigating VRE for specific phobias or PTSD. However, case studies or case series studies were also included when relevant in preliminary work with VRE in specific areas. The literature review was conducted using PsychInfo and reviewing all relevant published articles that focused on PTSD or any specific phobia. The authors also reviewed the references of the identified articles in order to identify any studies that may have been missed. The authors did not solicit unpublished data or include unpublished dissertations within the current review.

VR and Specific Phobias

According to the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition [13], specific phobias are characterized by "marked fear or anxiety about a specific object or situation (e.g., flying, heights, animals, receiving an injection, seeing blood)", that is out of proportion to the actual danger posed by the object/situation and is accompanied by active avoidance of it (or endurance with intense fear/anxiety). Recent epidemiological research found that specific phobia is the second most common mood or anxiety disorder in the USA, with a lifetime prevalence and morbidity risk rate of 15.6% and 18.4%, respectively [14]. The current gold-standard treatment for specific phobia is *in vivo* exposure, in which the patient directly confronts the feared stimulus, usually in a graduated manner, to promote extinction of fear through habituation and corrective learning. *In vivo* exposure treatment is highly effective in treating specific phobia, resulting in large effect sizes and superior results to nonexposure treatments in 1 to 5 sessions [15]. However, drop-out and treatment refusal rates for *in vivo* exposure are high, suggesting that alternative approaches are needed for those unwilling to try or tolerate this treatment [16]. One recent study found that more participants chose VRE than *in vivo* exposure for specific phobia when given a choice and that greater numbers refused treatment when offered *in vivo* exposure (27%) than VRE (3%), suggesting that VRE may be more palatable to potential patients [17]. Additionally, VR exposure for certain specific phobias (e.g., flying) may be more practical and less expensive to complete regularly on an outpatient basis.

Flying Phobia

At this time, 10 RCTs comparing VRE for flight phobia to other treatment conditions (both active and waitlist controls) have been performed [18–26]. Seven additional clinical trials have been performed, including 4 open trials or case series [27–30] and 3 within-subject randomized trials comparing different forms of or augmentations to VRE [31–33].

Findings from these RCTs suggest that VRE for flight phobia leads to significant reductions in the cognitive and physiological symptoms of fear, as well as reductions in behavioral avoidance in the real world (e.g., willingness to take a flight). VRE has consistently outperformed waitlist control conditions [21–23] and tended to outperform nonspecific attention control conditions, such as relaxation [20], bibliotherapy [18], and nondirective group therapy (although only on cognitive measures of anxiety [19]). Two trials have suggested that VRE may outperform imaginal exposure for flight phobia, perhaps due to leading to greater fear activation and habituation [24] and less avoidance [34], although both trials had small sample sizes. Furthermore, multiple RCTs have found most outcomes from VRE to be equivalent to those from *in vivo* exposure [22, 23, 26], although 1 study suggested that more participants receiving VRE used alcohol or drugs to cope with flying over a 12-month follow-up than those receiving *in vivo* exposure [35]. Almost all studies reviewed found robust treatment effects for VRE that were maintained over follow-up (1 month–3 years), and out of those trials that found reductions in effects following treatment, each found symptomatology was still lower than at pretreatment [19, 25]. Importantly, the effects of VRE appear to hold, regardless of whether motion simulation was included in treatment, indicating that visual and auditory simulation alone may lead to a sufficient experience of presence for effective activation and habituation of fear [21, 33]. In summary, most existing trials suggest that VRE for flight phobia results in significant and long-term reductions in cognitive, behavioral, and physiological symptomatology that are greater than those shown by nonspecific control conditions and similar to those shown after *in vivo* exposure, the gold-standard treatment.

Height Phobia

To date, 4 trials comparing VRE to other treatments or waitlist for acrophobia (fear of heights) have been performed [11, 36–38]. Two trials have found VRE to be superior to waitlist on all measures, including self-reported anxiety, behavioral avoidance, and attitudes towards heights [11, 38]. Krijn et al. [38] also compared VRE using a head-mounted display to a computer automatic virtual environment, a more immersive method that led to higher self-reported levels of presence among participants. While computer automatic virtual environment was associated with slightly fewer dropouts owing to insufficient activation of anxiety than head-mounted display, this difference was not statistically significant and outcomes were equivalent across both treatments, suggesting that the less expensive method of VRE may be sufficient for adequate treatment. An additional trial comparing VRE to *in vivo* exposure using matched stimuli (i.e., the same environments virtually and *in vivo*) found the 2 treatments lead to equivalent gains that were maintained over 6 months [37].

Five additional trials have been completed, including 2 within-group comparison trials [18, 39] and 2 RCTs comparing VRE augmented with D-cycloserine (DCS), a *N*-methyl-D-aspartate partial agonist shown to facilitate extinction in animal models, or placebo [40, 41]. Emmelkamp et al. [39] provided 2 sessions of VRE followed by 2 sessions of *in vivo* exposure to 10 participants with acrophobia and found that VRE led to such improvements that a ceiling effect occurred, leaving little room for additional improvement through *in vivo*. While the 2 RCTs found mixed results regarding the effectiveness of augmentation with DCS both found that VRE led to significant improvements, even at low doses (e.g., 2 sessions) [40–42]. Krijn et al. [18] found VRE to be effective regardless of whether the patient was instructed to use coping self-statements or not. In summary, while sample sizes have been small, extant studies suggest that VRE for acrophobia outperforms waitlist and leads to significant reductions in cognitive and behavioral symptoms with as few as 2 sessions and regardless of level of treatment adjuncts such as coping statements or higher-immersion VR systems.

Spider Phobia

Multiple open trials and RCTs have demonstrated significant effects of VRE for spider phobia. An early open trial found that 5 VRE sessions for spider phobia led to large and significant improvements in behavioral avoidance, information processing biases, and psychophysiological measures [43]. Similarly, a case series examining VRE treatment for spider phobia using a modified 3D computer game showed significant reductions in behavioral avoidance and maladaptive beliefs about spiders [44]. Subsequently, 2 trials have shown VRE for spider phobia to lead to significant improvements in self-reported anxiety and behavioral avoidance compared with waitlist controls [45, 46]. Additionally, 2 RCTs comparing VRE to *in vivo* exposure for spider phobia have been performed [47, 48]. Michaliszyn et al. [46] showed VRE and *in vivo* exposure for spider phobia were equally effective at improving self-reported fear of spiders and behavioral avoidance, although *in vivo* was more successful at improving self-reported beliefs about spiders than VRE. St-Jacques et al. [47] found that VRE and *in vivo* exposure led to similar behavioral outcomes in a small sample of children undergoing treatment for spider phobia.

An elegant series of studies by Shiban et al. [48–50] demonstrated how VR technology can provide an ideal medium for testing mechanisms of extinction learning and exposure therapy in a controlled environment. In the 2013 study by Shiban et al. [48], participants with spider phobia were randomized to either receive exposure in one context (a virtual room) or multiple contexts (a virtual room with different-colored lighting during each exposure trial). The results indicated that self-reported fear, skin conductance, and behavioral avoidance all showed greater reductions in the multiple context condition immediately following the 1-session treatment than in the single-context condition. In their next study, Shiban et al. performed a 2 × 2 RCT that randomized spider-phobic participants receiving VRE according to context (1 virtual room *vs* multiple) and stimuli (1 virtual spider *vs* multiple) [50]. This study also found that multiple contexts during exposure (regardless of stimuli) led to better outcomes in the short term; however, multiple stimuli combined with a *single* context led to the best outcomes in the long-term. Additionally, Shiban et al. [49] were able to test whether reactivation of fear prior to VRE led to greater therapeutic gains, a phenomenon demonstrated in previous animal studies. While no differences between groups were found in this study, neither group experienced a spontaneous recovery of fear in the 24-h period following the 1-session treatment, providing further evidence of VRE's efficacy in this population. Overall, the use of VR technology for exposure allowed for precise delineation of therapeutic factors in these studies and allowed for the ability to control variables that could be easily confounded in real life.

In summary, VRE treatments for spider phobia have been shown to lead to robust reductions in cognitive, behavioral, and physiological indicators of fear that are maintained over follow-up in as little as 1 session. The effects of these treatments are similar to that of *in vivo* exposure with minor exceptions (e.g., less improvement in self-reported beliefs in 1 study [46]).

Other Specific Phobias

While no RCTs examining VRE for other specific phobias have been completed at this time, some case studies and therapeutic analog studies have suggested it may be effective for additional conditions. A case study by Botella et al. [51] described how EMMA's world, a VR environment built to be adaptable to many different situations depending on the patient's needs, was used successfully to treat a 70-year-old woman with a phobia of storms. A case series examining VRE for driving phobia showed efficacy for approximately half of participants, suggesting it may be a promising first-line treatment for some [52]. Another case series demonstrated efficacy of VRE for specific phobias in young people with autism spectrum disorder [53]. While not a clinical trial, a study on participants with claustrophobia demonstrated that perceptual information presented in a virtual environment (e.g., seeing a door close on you in a virtual room) effectively led to an increase in the activation of self-reported and physiological fear, suggested that VRE might be effective in this population as well [54]. While together these studies are promising, more controlled studies with larger sample sizes are needed to test VRE's effectiveness in a wider range of specific phobias.

Summary of Specific Phobia Literature

Extant research examining VRE for specific phobias has demonstrated promising results. VR treatment for flight phobia, height phobia, and spider phobia has consistently outperformed waitlist conditions and nonexposure control treatments, requiring relatively few sessions. Frequently, VRE has demonstrated equivalent outcomes to *in vivo* exposure, the gold-standard treatment [22, 26, 35, 37, 39, 47] with a few exceptions [23, 46]. Additionally, the gains experienced in VRE for specific phobia generalize to real-life behavioral change, as a review of clinical trials with post-treatment behavioral assessments suggests that patients receiving VRE demonstrate better performance on behavioral assessments than waitlist patients and no significant difference from patients receiving *in vivo* exposure [55].

However, it is important to acknowledge that most of the existing studies have small sample sizes, with treatments groups usually composed of < 20 participants and sometimes < 10 participants. Such small sample sizes limit generalizability, particularly of between-group comparisons, such as those contrasting different variants of VRE or comparing VRE to other active treatments. Furthermore, most studies do not include long-term follow-up (1 year or more) of participants, although those that did tended to show that most treatment effects were maintained or improved, (with 1 exception [25]). In particular, studies examining treatment of phobias other than flight phobia and spider phobia are very few and most have small and uncontrolled samples, from which little can be generalized. However, some existing studies do highlight the unique beneficial features of VRE, including higher treatment acceptance, lower expense, and greater customizability than *in vivo* exposure. Research with larger sample sizes, particularly when comparing active treatments, is needed, as are longer follow-up periods. Furthermore, while VRE may be effective in treating storm phobia, claustrophobia, and driving phobia, controlled studies are needed.

PTSD

Within the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition, a diagnosis of PTSD requires exposure to a traumatic event and symptoms from each of the 4 PTSD symptom clusters, including intrusive symptoms, avoidance symptoms, negative alterations in cognitions and mood, and alterations in arousal and reactivity [13]. Epidemiological data from the USA indicates that PTSD has a lifetime morbid risk and 12-month prevalence rate of 10.1% and 3.7%, respectively [14], suggesting that this disorder represents a significant disease burden. As noted previously, PTSD is an apt example of a learned fear disorder, as conditioned fear to previously neutral stimuli associated with the traumatic event fail to extinguish over time leading to pathological and excessive conditioned fear responses to trauma cues. As such, PTSD can be conceptualized as a disorder of extinction, in which the failure of natural recovery of fear responses are related to a peritraumatic overburden of fear followed by a failure of fear extinction following the trauma. As such, it is a prime candidate for application of extinction learning principles, and consistent with this notion, extant research provides the strongest support for exposure-based interventions for PTSD treatment [56]. The use of VR technology within PTSD treatment provides the opportunity to conduct exposures that may not be possible otherwise, such as virtual Iraq and Afghanistan, and offers another treatment option that may be appealing to a video generation.

The extant empirical literature provides support for the efficacy of VRE for PTSD. Overall, VRE is related to a significant reduction in PTSD symptoms, performs significantly better than waitlist controls, and performs comparably to standard exposure therapy [57, 58]. Results suggest that patients report high acceptability and satisfaction regarding the use of VR technology within PTSD treatment [59, 60]. Early empirical investigation of this treatment was conducted using case study and series methodology. For instance, the first use involved a treatment-resistant Vietnam combat veteran who was exposed to 2 different environments, including a virtual helicopter flying over Vietnam and a clearing surrounded by jungle, and experienced a 34% decrease in clinician-rated symptoms and a 45% decrease in self-reported symptoms, providing preliminary evidence for the feasibility and efficacy of this approach [61]. Promising reductions in PTSD symptoms within VRE have been reported for a case study of a World

Trade Center attack survivor [62], a survivor of a deadly terrorist bulldozer attack [63], an Operation Iraqi Freedom veteran [64], and a military service member who experienced combat trauma [65].

Several uncontrolled case series studies have provided promising preliminary support for using VR technology for extinction training within PTSD. In an uncontrolled case series of motor vehicle crash survivors ($n = 6$), 10 sessions of VRE was associated with significant reductions in PTSD symptoms [66]. An uncontrolled case series in a sample of 6 active duty members of the Navy with combat PTSD found signification improvements, including reductions in PTSD, depression, and anxiety symptoms [67]. Another uncontrolled case series ($n = 10$) of combat veterans *in theater* found that both VRE and traditional exposure therapy results in significant improvement in PTSD symptoms [68], providing preliminary support of the feasibility and effectiveness of using VRE in combat theater. Notably, secondary analyses of these 2 military PTSD case series [67, 68] found that VRE for PTSD also resulted in significant improvements with regard to anxiety severity and performance on an the emotional Stroop test, a neuropsychological task using emotionally charged and trauma relevant words, while measuring reaction time and cognitive processing [69], providing evidence for effectiveness beyond PTSD specific symptoms. Across 2 trials on VRE for Vietnam veterans with PTSD ($n = 21$), significant reductions in PTSD were found, and notably these changes persisted at a 6-month follow-up assessment [70]. In a comparison of VRE ($n = 13$) with waitlist control ($n = 8$) in World Trade Center Attack survivors, the VRE group demonstrated a significantly greater decline in clinician-rated PTSD scores [71]. VRE resulted in a large effect size with regard to PTSD symptom improvement, which is particularly notable as 5 of the VRE participants had previously completed other PTSD treatment that did not result in meaningful improvement. This study provides preliminary support for VRE as a beneficial intervention for treatment nonresponders. The participants also had varying traumatic experiences, including firefighters, disaster workers, and civilians, exposed to the World Trade Center attack in varying manners, providing support to the idea that the VRE can effectively emotionally engage a variety of individual and specific traumatic experiences.

The first randomized trial to compare VRE for PTSD with an active treatment involved a comparison with present-centered therapy for Vietnam veterans ($n = 11$). No significant differences were found across the groups, but VRE demonstrated a moderate advantage at a 6-month follow-up assessment. As noted by the authors, the lack of a significant difference post-treatment was likely related to the small sample size and insufficient power. In a randomized trial comparing VRE for PTSD with treatment as usual in active duty military personnel, the VRE group demonstrated significantly greater reductions in PTSD symptoms [72, 73]. Notably, treatment-as-usual consisted of several different approaches; as such, there was likely variability in what patients received. Recently, a RCT compared VRE, PE, and a waitlist control in active duty soldiers with PTSD who had been deployed to Iraq and Afghanistan ($n = 162$) [74]. Both VRE and PE demonstrated significantly more improvement on PTSD and depressive symptoms relative to waitlist control. No significant differences were identified at post-treatment, but contrary to authors' hypotheses, PE demonstrated greater improvement in PTSD symptoms at the 3- and 60 month follow-up compared with VRE. The study did not assess variables related to the patient's subjective experience of the virtual environment or their degree of presence or emotional activation related to the environment. The authors note that there may have been variation in how activating patients found the virtual environment, and that increased options in the VR software may lead to better VRE outcomes in the future.

Two studies have investigated VRE for PTSD augmented by pharmacological agents thought to either facilitate or impede the fear extinction process. A double-blind randomized trial investigated the effectiveness of VRE for PTSD augmented with D-cycloserine, which has been found to facilitate extinction in other fear-based disorders [40], or alprazolam, an anxiolytic, *versus* placebo in a sample of Iraq and Afghanistan combat veterans ($n = 156$). Across all groups, VRE treatment resulted in significant PTSD symptom improvement at post-treatment, and at 3-, 6-, and 12-month follow-up assessments, despite being purposely underdosed at only 6 sessions. Notably VRE resulted in improvement in psychobiological measures of startle and cortisol reactivity to a trauma-relevant scene, providing further support for the effectiveness of extinction training within VR approaches. Another randomized trial compared VRE for PTSD with placebo and with D-cycloserine in World Trade Center survivors [75]. Both groups demonstrated significant decreases in PTSD symptoms at post-treatment compared with baseline, although the DCS group demonstrated greater improvements in both PTSD and secondary measures, providing further support for the efficacy of VRE for PTSD.

VRE has also facilitated clinical research findings in addition to treatment effectiveness. Additional research findings with regard to VRE and extinction training have been identified above and beyond investigating treatment effectiveness. For instance, within the trial of VRE for Iraq and/or Afghanistan veterans [76], results from cross-lagged panel design analyses suggest that re-experiencing symptoms at mid-treatment demonstrated a significant effect on the 3 other PTSD symptom clusters (avoidance, numbing, and hyperarousal), while controlling for symptom levels at the previous time point [77]. Re-experiencing symptoms demonstrated the largest standardized reduction across VRE treatment. This is consistent with the process of extinction learning, as fear conditioning leads to stimulus-danger associations that are elicited by a wide range of stimuli (e.g., re-experiencing symptoms). This finding also suggests that VRE effectively targets re-experiencing symptoms within PTSD treatment. Consistent with animal fear-conditioning models, physiological reactivity to trauma cues has been proposed as an objective marker of post-traumatic stress symptoms [78]. In this same veteran sample, baseline startle responses to VR trauma-relevant cues predicted greater improvement in PTSD symptom severity over time for the D-cycloserine group [78]. This suggests that increased engagement with the feared VR stimuli, coupled with cognitive-enhancing properties of D-cycloserine, may enhance the extinction training process within VRE. Physiological reactivity to trauma cues was assessed in another study in 58 veterans while they were exposed to standardized VR combat-related stimuli [79]. Groups included veterans with PTSD, veterans who were trauma-exposed but did not have PTSD, and veterans without trauma exposure or PTSD, and results indicated significant differences in physiological arousal across the groups. This provides support for the relevance of extinction learning with VRE, suggesting that virtual stimuli are able to represent meaningfully feared stimuli and engage conditioned fear responses. Additionally, classification accuracy was well above chance, suggesting that physiological activation while viewing standardized VR stimuli provides meaningful data regarding PTSD symptoms and could be used as an objective assessment or outcome within clinical and experimental research.

Summary of PTSD Literature

Overall, the extant literature suggests that VRE for PTSD results in significant reductions in PTSD symptoms and superior outcomes compared with waitlist control conditions. Past studies also suggest that VRE typically results in comparable outcomes with standard exposure-based interventions for PTSD (e.g., prolonged exposure). However, significant variability with regard to methodological rigor across VR PTSD studies has been noted [80]. Additionally, PTSD is frequently comorbid with other psychiatric disorders [81], but many studies do not provide information related to pre- and post-treatment comorbid conditions or symptoms. Future research on VRE for PTSD should include assessment of treatment impact on other commonly occurring comorbid symptoms, as this might reveal additional effects of treatment, or, conversely, cautions.

Limitations, Future Directions, and Conclusion

Several limitations to the use of VRE and the extant literature exist. First, disadvantages of VRE for specific phobia include the initial cost, the possibility of technological glitches, and the additional training required for providers to be able to use proficiently and skillfully the VR programs during treatment. Notably, the cost for VR equipment has decreased significantly in recent history, making it significantly less cost-prohibitive for use within clinical research and practice. For instance, there is now a VR system that can be used with a smartphone or personal computer that costs approximately $700; more cost-effective options such as this provide more opportunity for dissemination of VRE and access to VR equipment. The software has also improved significantly in recent years, improving both the usability and potential patient experience. As noted in the previous sections, the empirical literature surrounding VRE for specific phobia and PTSD does demonstrate limitations with regard to methodological rigor. VRE is not standardized across specific phobia or PTSD studies generally—the number of sessions can vary significantly (from 5 to 20 [57]), which is notable given that a meta-analytic review found that an increase in VRE sessions resulted in greater effect sizes with regard to treatment outcome [82]. Additionally, VRE often is one facet of treatment that may involve several other components, such as psychoeducation, anxiety management/coping skills, and cognitive restructuring. As such, dismantling studies could be beneficial to delineate more clearly the specific impact of VR within extinction training/exposure therapy. More research is also needed comparing VRE to standard exposure therapy, and to other active treatment approaches. Finally, many of the purported advantages of VRE and its consistency with extinction learning principles have not been directly empirically tested. Future research should focus on evaluating specific aspects of the therapeutic process as opposed to a continued emphasis on treatment outcome [83], and could empirically test proposed mechanisms of action within VRE.

It is notable that VRE provides several unique opportunities for conducting clinical research. Fear-based disorders are prime targets for translational methodology and approaches in psychiatry, as animal models and methods can directly inform psychiatric treatment. VRE provides an opportunity to conduct methodologically rigorous and controlled research. Specifically, VRE provides the ability to standardize exposure dose across participants, which is more difficult with traditional exposure therapy approaches. For instance, a recent RCT investigated if receiving a reminder of feared stimulus prior to VRE/extinction training would lead to greater reductions in fear of flying compared with receiving a neutral cue based on preclinical studies suggested that reconsolidation paradigms in animal models resulted in extinguished fear responses during extinction training [84]. This study utilized a translational extinction training paradigm and was able to implement controlled delivery of the reactivation/neutral cues within VR while also controlling the dose of VRE. VRE also provides an opportunity to include more objective assessment of treatment or experimental outcomes, such as physiological reactivity [79]. Consistent with this notion, standardized VR stimuli have been utilized as a measure of psychophysiological assessment pre- and post- VRE treatment for PTSD [76] and is being utilized in several PTSD treatment centers and laboratories across the country allowing for standardization of treatment response.

In summary, VRE is consistent with models of extinction learning and provides several advantages for use within exposure-based interventions. VR allows clinicians to engage patients in multisensory virtual environments specifically tailored to their feared stimulus in a controlled and customized fashion. These properties may lead to improved match of exposure material with feared stimuli and increased engagement, both of which are consistent with the goals of extinction learning and exposure therapy. It provides the ability to conduct extinction training/exposures for stimuli that may be too expensive or not feasible to conduct *in vivo*, such as virtual combat situations or multiple flights. Broadly, extant research provides support for the effectiveness of VRE in reducing symptoms of specific phobias and PTSD, with outcomes generally superior to waitlist controls and comparable with traditional exposure therapy [82, 85, 86]. With the cost of VR applications decreasing, it is likely that the use of VR within psychiatric treatment will only increase in the future, providing a high-quality treatment option for specific phobia and PTSD, as well as opportunities for well controlled psychiatric and experimental research.

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