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A Bioadaptive VR System for Exposure Therapy in Aviophobia

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***Abstract*—Aviophobia, or fear of flying, is a common anxiety disorder that can significantly limit individuals' mobility and quality of life. Exposure therapy is widely recognized as an effective treatment, but its application in real-world settings is often constrained by cost, accessibility, and lack of controllability. Virtual Reality (VR) offers a promising alternative by enabling safe, repeatable, and customizable exposure scenarios. This paper presents an immersive and therapist-controllable VR system for exposure therapy in aviophobia. The proposed system combines a realistic flight simulation with a modular architecture that enables real-time control of exposure parameters and has been designed to support future integration of bioadaptive mechanisms. A preliminary evaluation was conducted with 33 participants to assess usability, sense of presence, and potential adverse effects using standardized questionnaires. The results indicate a high level of engagement and perceived realism, with positive scores on spatial presence and ecological validity, and low levels of negative side effects. These findings support the feasibility and acceptability of the proposed approach as a foundation for VR-based exposure therapy. Future work will focus on integrating real-time biofeedback and validating the system in clinical settings to assess its therapeutic effectiveness.**

***Index Terms*—Aviophobia, Bioadaptive Systems, Exposure Therapy, Serious Games, Virtual Reality**

I. Introduction

Specific phobias (SPs) are characterised by persistent and excessive fear responses toward distinct stimuli, often leading to maladaptive avoidance behaviours that reinforce anxiety over time [18]. Among these, aviophobia (fear of flying) is particularly impactful, as it can significantly restrict personal mobility and quality of life. Exposure Therapy (ET) remains one of the most effective treatments for SPs, relying on controlled and repeated exposure to feared stimuli to promote habituation and reduce anxiety responses [2], [5], [13]. However, traditional in vivo exposure is often limited by practical constraints, including cost, safety, and the difficulty of recreating complex or rare scenarios such as flight-related emergencies.

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Virtual Reality Exposure Therapy (VRET) addresses many of these limitations by enabling controlled, repeatable, and ecologically valid exposure within immersive environments [3], [6], [17]. By simulating realistic contexts such as aircraft cabins or turbulent conditions, VR allows clinicians to manipulate environmental parameters with precision while maintaining a safe setting for patients. Despite these advantages, existing VRET systems often lack mechanisms to capture and adapt to the multidimensional nature of anxiety, which involves intertwined cognitive, physiological, and behavioural components.

To address this limitation, this paper presents a modular VR platform for exposure therapy in aviophobia that enables therapist-guided control of exposure conditions and has been designed to support bioadaptive extensions.

Biofeedback represents a promising approach for regulating emotional responses during exposure therapy. High-level biofeedback, such as affective labelling, has been shown to reduce emotional reactivity by encouraging individuals to verbalise their internal states [8], [9], [12], while low-level biofeedback enables the regulation of physiological signals such as heart rate or galvanic skin response [16]. When combined with VR-based exposure, these mechanisms support both emotional awareness and active regulation, contributing to more effective therapeutic outcomes [2], [5], [13].

Building on these principles, the proposed architecture has been designed to support future integration of real-time physiological sensing with adaptive control of the virtual environment. In future work, psychophysiological signals could be used to dynamically adjust stimulus intensity, for example by modifying turbulence, lighting, or auditory cues through therapist-guided or automated processes [14]. This approach transforms VR from a static exposure tool into an interactive and responsive system capable of tailoring therapy to individ-

ual users.

In this context, this paper presents the design and preliminary evaluation of a modular VR system for exposure therapy in aviophobia. The system consists of an immersive flight simulation environment combined with a modular control framework that supports both therapist-guided and AI-driven interventions. In particular, an AI-based Virtual Reality Exposure Therapy (AI-VRET) approach is envisioned, where reinforcement learning techniques are used to infer optimal exposure strategies from multimodal data [4], [7], [19].

This work makes three main contributions. First, it introduces a realistic and interactive VR environment specifically designed to simulate flight-related anxiety triggers. Second, it integrates this environment within a modular control architecture that enables therapist-guided manipulation of exposure conditions and provides a foundation for future bioadaptive adaptation. Third, it provides preliminary evidence on usability, presence, and acceptability, supporting the feasibility of the proposed approach as a foundation for adaptive VR-based exposure therapy.

II. Background & Motivation

A. Virtual Reality Exposure Therapy

Virtual Reality Exposure Therapy (VRET) has emerged as an effective extension of traditional exposure therapy for the treatment of anxiety disorders and specific phobias. By enabling controlled, immersive, and repeatable exposure to fear-inducing stimuli, VRET overcomes many limitations of in vivo approaches, such as cost, safety constraints, and limited accessibility [6], [17]. Through realistic simulations, virtual environments allow clinicians to manipulate exposure conditions while maintaining a safe setting for patients, making VRET a flexible and increasingly adopted therapeutic tool.

B. Applications Across Mental Health Conditions

VRET has been successfully applied to a variety of psychological conditions, demonstrating its versatility as a therapeutic tool. In the context of aviophobia, studies have shown that increasing realism through multisensory stimulation can enhance the sense of presence, which is closely linked to treatment effectiveness [15]. For example, the inclusion of tactile feedback and realistic motion cues can strengthen users' perception of being in a real flight scenario, thereby eliciting more authentic emotional responses. At the same time, the emergence of Online Virtual Reality Therapy (OVRT) has enabled remote and accessible interventions, allowing patients to undergo structured exposure sessions outside clinical settings while still achieving reductions in anxiety and avoidance behaviours comparable to traditional approaches [21].

More broadly, VRET has been widely used for other specific phobias, such as fear of heights or spiders, where controlled virtual exposure allows gradual and systematic desensitization. In these cases, VR enables precise manipulation of stimulus intensity for example, adjusting height levels or proximity to feared objects, supporting individualized progression and reducing the risk of overwhelming the patient [17]. VRET has also been applied to social anxiety disorders, where users can practice interactions in simulated environments ranging from small group conversations to large audiences. These scenarios allow repeated rehearsal of social behaviours in a safe context, contributing to improved confidence and reduced anxiety over time [10].

In addition, VRET has shown promising results in the treatment of PTSD and other anxiety-related conditions. Here, virtual environments are used to recreate trauma-related cues in a controlled and gradual manner, often following staged exposure protocols that increase in intensity over time. Adaptive and culturally tailored scenarios have been shown to improve engagement and therapeutic effectiveness, particularly in populations with complex trauma backgrounds [1]. Across these applications, the ability of VR to combine realism, controllability, and repeatability makes it a powerful platform for delivering exposure-based interventions.

C. Physiological Monitoring and Adaptive Approaches

A key development in recent VRET systems is the integration of physiological monitoring to support personalization. By tracking signals such as heart rate, skin conductance, or respiration, these systems can estimate users' emotional arousal and dynamically adjust exposure intensity in real time [17], [20]. For example, increases in physiological activation can be used to detect excessive stress, prompting the system to reduce stimulus intensity, whereas stable responses may allow for gradual progression to more challenging scenarios. This biofeedback-driven approach helps maintain patients within an optimal therapeutic window, balancing sufficient emotional engagement with safety and tolerability.

Such adaptive mechanisms represent a shift from static exposure scenarios toward responsive and closed-loop therapeutic environments. By continuously linking user state to environmental changes, these systems enable more precise and individualized interventions. In addition, physiological monitoring provides objective measures of user response, complementing subjective self-reports and supporting more accurate assessment of treatment progress. However, fully integrating these signals into reliable real-time adaptation strategies remains an open challenge, particularly when considering the variability and noise inherent in physiological data.

D. Challenges and Research Gaps

Despite its potential, VRET still faces several challenges that limit its widespread adoption. Technological barriers, including hardware cost, system variability, and issues such as cybersickness or discomfort, can reduce accessibility and user adherence [11]. These factors are particularly relevant in home-based or large-scale deployments, where consistent user experience cannot be guaranteed. Methodological limitations are also common in current research. Many studies rely on small and heterogeneous samples, short intervention periods, and non-standardized protocols, making it difficult to compare results across studies or assess long-term effectiveness [17].

Furthermore, outcome measures often depend heavily on self-reported data, with limited integration of objective physiological or behavioural metrics.

The incorporation of physiological monitoring introduces additional complexities. Sensor accuracy can be affected by motion artefacts, calibration issues, and individual variability, while the collection and processing of biometric data raise important privacy and ethical concerns [20]. Overall, these challenges highlight the need for more robust, scalable, and standardized approaches to VR-based therapy. In particular, there is a growing need for integrated frameworks that combine immersive environments, reliable physiological sensing, and adaptive control strategies within a coherent and clinically validated system.

E. Motivation for This Work

These limitations motivate the development of VR systems that can support future bioadaptive capabilities through the integration of real-time physiological feedback and computational models of anxiety. By dynamically adjusting exposure conditions based on the user's state, such systems have the potential to improve personalisation, safety, and therapeutic effectiveness. Building on this vision, this work presents a modular VR platform for exposure therapy in aviophobia that has been designed to support future bioadaptive extensions. Existing VRET systems for aviophobia primarily focus on delivering immersive exposure scenarios and evaluating their therapeutic effectiveness, often through predefined sequences of flight-related events or the incorporation of multisensory cues such as vibrotactile stimulation [15]. In contrast, the proposed system emphasises a modular and therapist-controllable architecture that enables flexible manipulation of exposure conditions in real time. Rather than implementing a fixed therapeutic protocol, the system has been designed as an extensible platform that supports future integration of physiological monitoring and AI-driven adaptation, providing a foundation for more personalised exposure therapy.

III. System Design

A. Design Objectives and Overview

The proposed system was designed as an immersive virtual reality environment for exposure therapy in aviophobia. Its main objective is to reproduce a realistic aircraft cabin in which flight-related anxiety stimuli can be introduced, intensified, and reduced in a controlled manner. The design follows three main principles: ecological validity, clinical controllability, and modularity. Ecological validity is achieved by recreating a believable flight scenario, while clinical controllability allows therapists or automated systems to manipulate exposure intensity in real time. Modularity ensures that individual components of the system can be independently controlled and extended, enabling future integration with adaptive and AI-driven mechanisms.

B. Virtual Environment and User Experience

The virtual environment was developed in Unity starting from a realistic aircraft cabin model, which was adapted and optimized for the purposes of the project. The original asset provided the main cabin structure, including seats, windows, overhead compartments, and lighting elements. Several modifications were introduced to improve both technical performance and clinical suitability. Non-essential components were simplified, while visually relevant elements were preserved to maintain realism. In addition, the colour palette of the cabin was adjusted following clinical feedback: bright colours were replaced with neutral tones to avoid unintentionally inducing calming or distracting effects during exposure.

To enhance presence, additional elements were incorporated into the environment. Animated passengers were added to simulate a realistic social setting, while an aircraft wing and engine were positioned outside the window to reinforce the perception of being on a real flight. The user experiences the environment from a seated first-person perspective through a VR headset, with head movements directly mapped to the virtual camera. Locomotion is intentionally disabled to reflect real flight conditions and to reduce the risk of disorientation. This design supports immersion while maintaining consistency with the therapeutic context.

C. Exposure Scenarios and Stimuli

The system supports a range of exposure scenarios designed to gradually induce and regulate anxiety. The environment can transition from calm flight conditions to more intense situations involving reduced lighting, rain, lightning, turbulence, rumbling sounds, passenger reactions, and emergency events such as oxygen mask deployment. These elements correspond to common anxiety triggers associated with flying and can be combined to create progressively more challenging scenarios (see Figs 1 and 2). Transitions between states are designed to be smooth and continuous rather than abrupt, preserving realism and avoiding unnecessary discomfort. This gradual modulation of stimuli is essential for exposure therapy, as it allows users to build tolerance while maintaining a sense of control. The ability to finely adjust environmental parameters enables both standardized and personalized exposure protocols.

D. Modular Architecture

The system architecture evolved from an initial timer-based prototype into a modular manager-based design. In the early version, events were triggered according to a predefined timeline, which limited flexibility and prevented real-time adaptation. In the final implementation, different aspects of the environment are controlled by dedicated modules responsible for lighting, weather, turbulence, emergency events, audio feedback, and emotional indicators. Each module operates independently while contributing to a coherent overall simulation. This modular approach enables real-time updates, simplifies system maintenance, and supports extensibility. It also provides the foundation for integrating external control



Fig. 1. Emergency scenario in the virtual aircraft cabin, showing the deployment of oxygen masks during high-intensity exposure conditions. The scene illustrates how critical events are simulated to elicit strong emotional responses in a controlled environment.

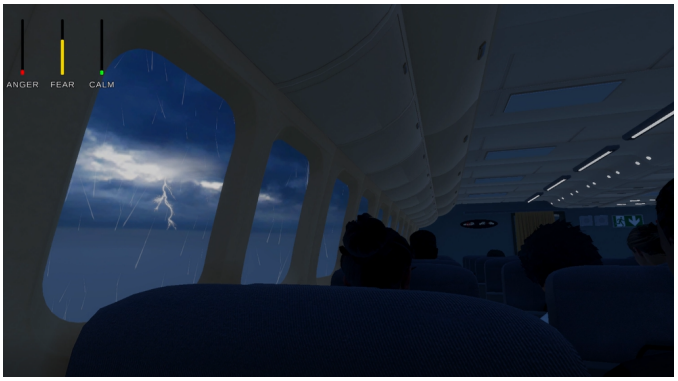


Fig. 2. Storm scenario in the virtual flight environment, featuring rain, lightning, and reduced visibility. Such conditions are used to progressively increase exposure intensity and simulate realistic anxiety-inducing situations.

mechanisms, allowing the environment to be dynamically adjusted during exposure sessions.

IV. System Integration

A. Hardware and Software Framework

The system integrates multiple tools and technologies to support the development and execution of the VR experience. The virtual environment was implemented in Unity using C#, while 3D assets were created and optimized in Blender. The application was deployed on a Meta Quest 3 headset, which provides stereoscopic visualization and six degrees of freedom head tracking. This setup enables an immersive and embodied experience while maintaining portability and ease of deployment.

B. Control Interface and Communication Layer

A central component of the system is the external control interface, developed as a web-based application using React. The interface allows therapists or researchers to manipulate environmental parameters in real time through intuitive controls such as sliders, switches, and selectors. These controls correspond to key aspects of the simulation, including lighting, weather conditions, turbulence, audio cues, and emergency events. Communication between the control interface and the VR environment is handled through a WebSocket-based architecture. Commands are encoded as lightweight JSON messages specifying the target parameter and the desired action. Within Unity, these messages are processed and dispatched to the corresponding modules responsible for updating the environment. This approach enables low-latency, bidirectional communication and ensures that the system can respond dynamically to external input.

C. Therapist-Guided Interaction

In its current configuration, the system operates in a therapist-in-the-loop mode. The clinician observes the participant's behaviour and adjusts the environment through the control interface (see Fig 3). The panel enforces logical constraints between parameters, ensuring that transitions remain realistic and clinically meaningful. For example, severe events are only enabled after appropriate escalation steps, preventing abrupt or incoherent changes in the simulation. This approach supports controlled and gradual exposure, allowing the therapist to tailor the session to the participant's needs while maintaining consistency with therapeutic protocols.

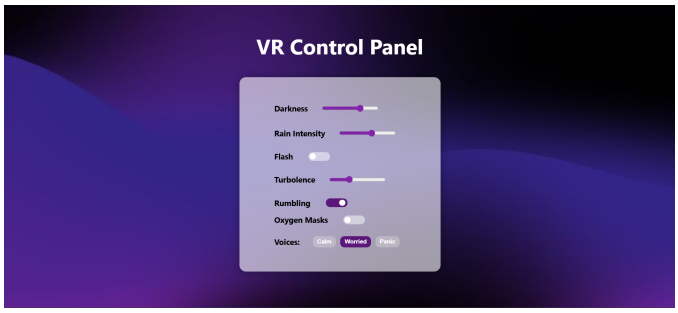


Fig. 3. Web-based control panel used to manipulate exposure parameters in real time. The interface allows therapists or AI agents to adjust environmental conditions such as lighting, turbulence, weather effects, and soundscape during VR sessions.

D. Adaptive Integration and Future AI Control

The system architecture is designed to support future integration with adaptive and AI-driven control mechanisms. In this scenario, physiological and behavioural data collected during the session can be used to estimate the participant's emotional state. An AI agent can then generate control commands to dynamically adjust the environment, using the same communication protocol as the therapist interface. This enables a closed-loop interaction in which the user's responses influence the environment, and the environment in turn influences the user's emotional state. Such an approach has the potential to improve personalization and optimize exposure therapy by continuously adapting to individual needs.

E. Reliability and System Safety

To ensure stability and safety, the system incorporates several mechanisms at both the communication and environment

levels. Commands are validated before execution, redundant triggers are suppressed, and parameter values are constrained within safe ranges. Environmental transitions are implemented using smoothing and interpolation techniques to avoid abrupt changes, visual artifacts, or audio discontinuities. These safeguards are particularly important in a therapeutic context, where the system must remain predictable and controllable even during high-intensity exposure scenarios. Overall, the integration pipeline provides a robust and flexible framework that supports both current therapist-guided sessions and future adaptive therapeutic approaches.

V. Evaluation

A. Participants and Procedure

A total of 33 participants took part in the evaluation study, spanning different age groups and exhibiting heterogeneous levels of familiarity with digital technologies and virtual reality. Background information collected prior to the experiment indicated that most participants were familiar with air travel, with the majority reporting more than ten flights in their lifetime. While only a subset reported moderate fear of flying, variability was observed in sensitivity to intense experiences and susceptibility to motion sickness. Additionally, 72.3% of participants had prior experience with VR systems, while the remaining participants were first-time users. This diversity provided a suitable sample for capturing a wide range of perceptual responses.

Each participant experienced the same virtual flight simulation using a Meta Quest 3 headset in a seated, first-person configuration. The simulation followed a controlled escalation–de-escalation sequence lasting approximately 4–5 minutes, progressing from a calm baseline to a peak emergency scenario (including turbulence, storm conditions, and oxygen mask deployment) before returning to normal flight conditions. This standardized protocol ensured consistency across participants. Immediately after the experience, participants completed the ITC-SOPI questionnaire, which evaluated four dimensions of user experience: spatial presence, engagement, ecological validity (naturalness), and negative effects. Scores were computed on a 1–5 Likert scale and averaged for each dimension. All participants provided informed consent before taking part in the study and were informed about the purpose of the experiment, the nature of the VR experience, and their right to withdraw at any time without penalty. The exposure followed a gradual escalation and de-escalation sequence, participants remained seated throughout the session, and a researcher supervised each session. Participants were informed that they could stop the experiment and remove the headset at any time if they experienced discomfort.

B. Quantitative Results

Table I reports the average ITC-SOPI scores across all participants. The results indicate a generally positive perception of the virtual experience, with all perceptual dimensions scoring above the midpoint of the scale.

TABLE I
Average ITC-SOPI scores across all participants (n=33).

Dimension	**Mean ± SD**
Spatial Presence	3.20 ± 0.66
Engagement	3.71 ± 0.64
Ecological Validity	3.70 ± 0.59
Negative Effects	1.62 ± 0.62

Engagement and ecological validity achieved the highest scores, reflecting the effectiveness of the scenario design and multisensory cues in sustaining user involvement. The negative effects dimension remained low, indicating minimal discomfort or cybersickness across participants. Variability across users was moderate, reflecting differences in individual sensitivity and prior experience, but no extreme adverse reactions were observed. Overall, the results suggest that the system can induce meaningful emotional responses while maintaining a comfortable and safe experience.

C. Qualitative Feedback

Participants also provided open-ended feedback, offering insights into both strengths and areas for improvement. Positive comments consistently highlighted the realism of the simulation, particularly the weather dynamics, turbulence effects, and spatial audio design. Several users reported positive sense of presence, describing moments in which they felt as if they were inside a real aircraft. The behaviour of virtual passengers and the progression of the scenario were also identified as important contributors to emotional engagement. Constructive feedback mainly focused on enhancing interactivity and realism. Participants suggested introducing more dynamic passenger behaviours, smoother transitions between environmental states, and additional interaction capabilities such as hand tracking or object manipulation. Some users also expressed interest in more personalised experiences, for example adaptive scenarios or supportive virtual elements to modulate anxiety.

D. Discussion

The evaluation results indicate that the proposed VR system successfully achieved its primary objectives of immersion, engagement, and realism, while maintaining low levels of discomfort. The relatively high engagement and ecological validity scores suggest that the environment is suitable for eliciting emotionally meaningful responses, which are essential for exposure-based interventions. Qualitative feedback suggested that participants with prior VR experience were more likely to comment on technical aspects such as graphical fidelity and transition smoothness, whereas participants with less VR experience more frequently described the novelty and emotional impact of the simulation. Some participants who self-reported a greater sensitivity to intense experiences or a mild fear of flying also described feeling highly engaged by

the simulation. However, these observations are qualitative and should not be interpreted as evidence of differences between participant groups. Overall, these findings support the feasibility of the proposed approach and highlight several directions for improvement, particularly in terms of interactivity, social realism, and adaptive personalisation. These aspects represent promising avenues for future development within the broader framework.

VI. Conclusions and Future Work

This paper presented the design and preliminary evaluation of a bioadaptive VR system for exposure therapy targeting aviophobia. The system aims to provide a realistic, controllable, and flexible virtual environment capable of supporting exposure-based interventions while enabling multimodal data collection. The results demonstrate the feasibility of using immersive VR as both a therapeutic and experimental platform. The proposed environment successfully reproduces key perceptual and emotional aspects of a flight scenario, offering a safe yet engaging context for eliciting anxiety-related responses. The integration of a real-time control interface allows dynamic manipulation of exposure parameters, enabling both therapist-guided and adaptive interventions. The evaluation further indicates that the system achieved good levels of presence, engagement, and ecological validity, while maintaining low levels of discomfort. From a broader perspective, this work contributes to the development of data-driven and personalised digital therapeutics. By supporting continuous monitoring and modulation of environmental conditions, the system establishes the foundation for a closed-loop interaction between user state and virtual stimuli, which is essential for adaptive exposure therapy and for the validation of computational models of phobia dynamics.

Future work will focus on extending the system along three main directions. First, further technical and design improvements will aim to enhance realism and user interaction, including more dynamic virtual agents, smoother audiovisual transitions, and increased interactivity through hand tracking and object manipulation. Second, the integration with the AI-VRET framework will enable automatic adaptation of exposure conditions based on real-time psychophysiological data, leveraging reinforcement learning techniques to optimise therapeutic strategies. Finally, the system will be evaluated in larger-scale experimental and clinical studies to assess its effectiveness across different exposure modalities and to validate the proposed adaptive approach in real-world therapeutic settings. Overall, the proposed system represents a promising step toward scalable, adaptive, and personalised VR-based exposure therapy, contributing to providing a flexible platform for future bioadaptive interventions and supporting the translation of immersive technologies into clinical practice.

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