ISSN 2616-5791 Vol. 7, Issue 3: 73-82, DOI: 10.25236/AJMHS.2026.070310

The Effect of VR Games and MDA Framework on Post-Traumatic Stress Disorder (PTSD) after Car Accidents

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Abstract: *Post-traumatic stress disorder (PTSD) is a mental health condition triggered by extremely stressful or terrifying events — either being part of or witnessing them [9]. Symptoms may include flashbacks, nightmares, severe anxiety, or uncontrollable thoughts about the event [9]. Among the many events that can lead to PTSD, road traffic accidents (RTA) account for a significant share. Current solutions for PTSD include psychotherapies, pharmacotherapy, cognitive behavioral therapy, and prolonged exposure therapy [7]. While these methods have proven to be effective, studies have demonstrated that some participants find the treatments to be "too stressful [6]." A few other barriers to traditional PTSD therapies include limited access to therapists trained in trauma-focused therapy, survivors who may not wish to use conventional treatments, or cost and insurance coverage concerns [6]. This study introduces a Unity-powered virtual reality rehabilitation game that integrates the MDA (mechanics-dynamics-aesthetics) framework to create a safe, controllable, and immersive environment for individuals with PTSD to undergo gradual trauma recovery. Unlike existing virtual reality exposure therapy (VRET) systems, gamified experiences are used effectively to target psychological responses to trauma — specifically, to create a sense of safety and controllability alongside manageable anxiety. Four versions of the game were tested on 14 healthy participants: a complete MDA version as well as three variants lacking one framework element each. Quantitative results show that the full MDA version achieved the lowest mean anxiety level and the highest reported safety and self-efficacy. These findings demonstrate that the MDA framework serves as an effective tool for structuring therapeutic VR experiences, laying the necessary groundwork for its future application in clinical PTSD treatment.*

Keywords: *Post-traumatic stress disorder; Virtual reality; MDA framework; Exposure therapy; Gamification*

1. Introduction

Post-traumatic stress disorder (PTSD) is a mental health condition that develops after exposure to traumatic events beyond a typical stressor [18]. Events that may lead to PTSD include, but are not limited to, violent personal assaults, natural or human-caused disasters, accidents, combat, and other forms of violence [18]. People who experience PTSD may have persistent, frightening thoughts of the event(s), sleep issues, feelings of detachment or numbness, or startle easily [18]. In severe forms, PTSD can significantly impair a person's ability to function at work, at home, and socially [18]. While most adults – nearly 70% - experience at least one traumatic event in their lifetime, only about 20% develop PTSD [5]. Nevertheless, about 6% of the U.S. population experiences PTSD at some point in their lives, and an estimated 3.9% of the world population is affected, highlighting the importance of developing effective PTSD therapies [15,16,19].

Among the causes of PTSD, road traffic accidents are one of the most common sources. Over 50 million people worldwide experience RTA yearly, and a meta-analysis of 69 studies involving 16,977 RTA participants across five continents found that the pooled frequency of PTSD was 26%, meaning that 1 in every 4 RTA survivors develops significant post-traumatic symptoms [2,12,21]. Thus, RTA-related PTSD is an urgent issue that this study intends to address.

Conventional treatments for PTSD include psychotherapies, pharmacotherapy, cognitive behavioral therapy, and prolonged exposure therapy [7,13]. While these methods have proven to be effective, studies have demonstrated that some participants find the treatments to be "too stressful [6]." A few other barriers to traditional PTSD therapies include limited access to therapists trained in trauma-focused therapy, survivors who may not wish to use conventional treatments, or cost and insurance coverage concerns [6]. Virtual reality exposure therapy (VRET) is a form of exposure therapy that uses virtual reality technologies to address some of these limitations [1-2]. VRET allows patients to immerse themselves in a 3D, interactive environment through a VR headset that closely simulates the traumatic event or related stressors, providing a controlled and repeatable experience [3]. Patients can face their fears in a controlled and safe environment, and controlled exposure helps them to desensitize and gradually reduce their emotional response to these triggers [3,6]. Despite promising results, most VRET solutions focus primarily on exposure efficacy and overlook the design quality of the therapeutic experience itself.

MDA is a formal approach to understanding games, one that attempts to bridge the gap between game design, development, criticism, and technical research [10]. The MDA framework comprises three aspects: mechanics, dynamics, and aesthetics [10]. Mechanics describes the particular components of the game at the level of data representation and algorithms [10]. Dynamics describes the run-time behavior of the mechanics acting on player inputs and each other's outputs over time [10]. Finally, aesthetics describes the desirable emotional responses evoked in the player when she interacts with the game system [10]. When describing the aesthetics of a game, the design tends to focus on a specific vocabulary word, such as "challenge" or "experience [10]." This study introduces a novel approach that integrates the MDA framework with VRET approaches to develop an effective PTSD rehabilitation system that enhances patients' sense of safety, control, and emotional regulation, establishing a promising foundation for future clinical applications.

2. Background and Related Work

2.1 Neurobiological Perspective on PTSD

PTSD has affected military members, trauma survivors, and victims of violence for many generations. Unlike other anxiety-related disorders, PTSD is a deeply neurobiological disorder with consequential influences on a person's brain. In a research paper titled *Neurobiological Features of Posttraumatic Stress Disorder (PTSD) and Their Role in Understanding Adaptive Behavior and Stress Resilience*, researchers explore the neurobiological aspects of PTSD [16]. They discuss how PTSD is deeply intertwined with dysfunctions in the prefrontal cortex (PFC) [16]. The prefrontal cortex is associated with executive functions, playing a crucial role in decision-making, the processing of intrinsic and extrinsic sensory information, and overall behavior [16]. In a recent narrative review on neuroanatomical components involved in emotional regulation in PTSD, Fitzgerald et al. (2018) describe an overall under-engagement of prefrontal areas during emotional processing in individuals with PTSD [16]. This is caused by high levels of stress that lead to hypoactivation in the PFC [16]. The PFC can be subdivided into different sections: ventromedial PFC (vmPFC), medial PFC (mPFC), and the dorsolateral and ventrolateral PFC (dlPFC and vlPFC) [16]. The vmPFC is involved in emotional processing, serving as an extensive, interconnected area of the PFC associated with decision-making and the perception of self [16]. In many experiments exploring the functional neuroanatomical components of mental health conditions, patients experience decreased activation of the left vmPFC, affecting their ability to self-regulate negatively triggered emotions that lead to decision-making deficits and behavioral abnormalities, recognized as exaggerated reactions to environmental triggers in PTSD patients [16].

2.2 Gamification in Mental Health Treatments

Gamification – the integration of game elements into non-game contexts – has increasingly been applied to treatments for psychiatric disorders such as PTSD. In a 2023 study titled *Gamification: A Novel Approach to Mental Health Promotion*, researchers report that carefully designed and executed gamified mental health interventions can optimize treatment effectiveness and suitability for meeting clients' individual needs and preferences [4]. In another study titled *Digital Gaming Interventions in Psychiatry: Evidence, Applications and Challenges*, Digital Mental Health Interventions utilize the principles of gamification to manage the psychological and social domains of various psychiatric disorders [4]. Gamification is a novel approach that incorporates gaming elements to enhance treatment adherence, boosting patients' motivation to engage with the treatment and comply with the regimen [4].

2.3 Virtual Reality Exposure Therapy (VRET)

Virtual reality exposure therapy (VRET) has demonstrated substantial improvements in treatment compared to traditional methods. In a 2017 study, Maples-Keller et al researched the use of virtual reality

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technology in the treatment of anxiety and other psychiatric disorders, including PTSD [8]. Findings suggest that patients report satisfaction with VR-based therapy and may find it more acceptable than traditional approaches [8]. An early study on VRET in patients with PTSD due to motor vehicle crashes showed that patients reported very high satisfaction with these approaches [15]. In a sample of 150 patients with specific phobias, the refusal rate for VR exposure (3%) was lower than for in-vivo exposure (27%), providing preliminary evidence that VR-based exposure may be more acceptable to patients [15]. In a sample of 352 post 9/11 US soldiers, the majority reported that they would be willing to use most of the technology-based approaches for mental health care included in the survey (e.g., VR) [8].

Additionally, 19% of those who reported that they would not be willing to talk to a counselor in person reported being willing to use VR approaches to access mental health care, suggesting VR may address some of the barriers to treatment [8]. A 2011 meta-analysis of VRET by Opriş et al. confirmed the efficacy of VRET in the treatment of anxiety disorders [17]. They reported that VRET performs significantly better than the waitlist control, and it also has a profound real-life impact, as well as stability of results over time [11].

While many existing VRET systems incorporate gamification elements (such as scores, rewards, and progress bars), a critical gap in the literature is that **few are grounded in formal game design theory.** In contrast, this study's innovation lies in **systematically integrating the MDA framework into the design pipeline of therapeutic VR**, aligning low-level mechanisms (stimuli and user interactions), emergent dynamics (challenge, pacing, and feedback loops), and aesthetic/emotional outcomes (immersion, emotional safety, and flow) with the therapeutic objectives. **In a 2021 study titled *Immersive Virtual Reality Health Games: A Narrative Review of Game Design*, researchers conclude that** more in-depth and structured attention to how HMD-VR health games are designed is needed [14]. Another study titled *CFI: A VR Motor Rehabilitation Serious Game Design Framework Integrating Rehabilitation Function and Game Design Principles with an Upper Limb Case* points out that there remains a notable lack of in-depth research on VR rehabilitation serious game design methods[20]. The pattern consistent in both studies shows that while VR games exist, they lack a foundational basis in gamification.

2.4 MDA Framework

According to multiple studies, MDA is particularly effective in therapeutic game design. A 2022 research titled *Development of a Therapeutic Video Game With the MDA Framework to Decrease Anxiety in Preschool-Aged Children With Acute Lymphoblastic Leukemia: Mixed Methods Approach* by Yang et al. utilized the MDA framework to treat anxiety-based psychiatric disorders. Their results showed that therapeutic video games implementing the MDA framework effectively decreased anxiety in their target audience. However, studies have also pointed out that while there is an increasing emphasis on the gamification element in many research studies, they often overemphasize efficacy while lacking a rigorous evaluation phase for the design quality and user experience of therapeutic VR systems themselves [14]. To target these gaps in current solutions, this study combines VRET with the MDA framework while also emphasizing an intricate experimentation stage to achieve more effective means for PTSD symptom alleviation.

3. Methodology

Platform and Hardware. The development platform used in this project is Unity 3D, chosen for its flexibility in creating immersive 3D environments and compatibility with major VR frameworks. Unity projects can be integrated with SteamVR/OpenXR and the XR Interaction Toolkit, enabling precise editing and calibration. C#, Unity's scripting language, is used to develop the software for this project. The hardware used for VR simulation is the Pico 4 headset and its corresponding motion controllers. Upon completing the major scenes, the project was deployed to Pico 4 for real-time testing and refinement.

MDA-Driven Design. The game is designed using the MDA framework to achieve safety, controllability, and a gradual emotional exposure experience. To target the mechanical aspect of MDA, the selected VR platform must ensure effective movement, interaction, and controllability. Using the XR interaction toolkit, players can pick up car components while maintaining flexible movement within the game. The toolkit also allows players to grab and place objects however they like, with minimal restraints. In the following section of the game, players will then place the grabbed components onto a central display, either by gently releasing the controller's button or by throwing the object, as shown in Figure

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1.

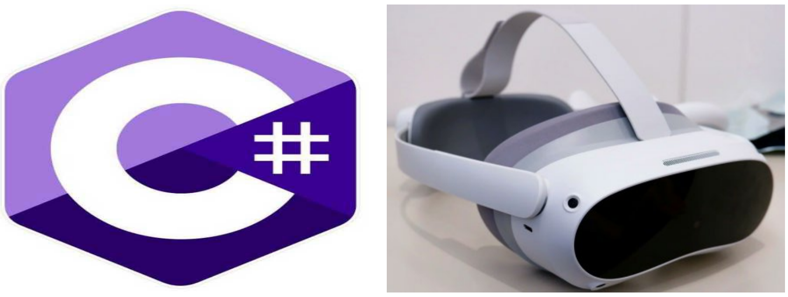

Figure 1: C# Development Environment (left) and Pico 4 VR Headset (right)

Game progression adopts an unlock-based sequence design. Players in the safe room unlock access to the following exposure level scenario by completing specific tasks, such as finding and returning a car component. The player presses the start button, triggering a signal to “unlock” the first door. The player then returns the first component, “unlocking” access to the second door, so on and so forth. As a result, the players gain a sense of agency and control over the procedure, allowing them to decide when to proceed, mirroring the principles of gradual exposure therapy. Only when they are prepared to enter a new hall, or metaphorically, a new stage, will the doors open and allow them to advance, as shown in Figure 2.

Figure 2: Safe Room Environment and Car Components for Task-based Progression

Moving on to dynamics, a gradual emotional experience is emphasized. As mentioned earlier, the opening of the doors is a controlled and gradual aspect of the game: the specific order in which the doors open is carefully designed. For example, the first door consists of no pictures, the second consists of one image of a car accident scene, and the third consists of two, and so on. By providing players with a gradual exposure to the things they are afraid of, players can better cope with their PTSD triggers. In addition, the assembly of the car also demonstrates this gradual exposure to their fear: when a component is placed, such as a wheel, all four wheels on the vehicle appear; when a car light is placed, all four car lights appear. After the player has collected and returned all four components, a complete car is assembled. In this way, the players are first exposed to only one car component, to two car components, and finally, a whole car. This demonstrates the gradual exposure crucial to the dynamic aspect of the MDA framework, as shown in Figure 3.

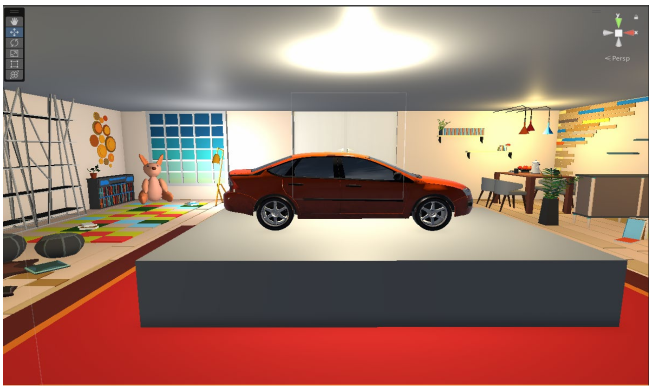

Figure 3: Complete Car Assembled after Successful Gameplay

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The aesthetics dimension of the MDA framework refers to the emotional shifts that players experience throughout the game. At the start of the game, the player is expected to feel a sense of anxiety and fear as they face their traumas. As they enter the game, they spawn in a cozy and safe room interior, with peaceful music playing in the background, designed to reduce their anxiety and instill a sense of safety. When they enter the first hall, they experience a shift in environment, from a warm, cozy, and bright room into dark halls devoid of decoration. Upon entering, an audio recording detailing road traffic accidents associated with the component will be played, evoking a sense of anxiety that is controlled and restrained, as no pictures are present. After grabbing the component, they return to the center room, where they are in a safe environment, and then return the component. Another audio will be played, one that inspires players and provides hope, contrasting with the previous audio. This process is repeated four times until, at the end of the game, the players are predicted to have a better ability to cope with their traumas and feel less anxiety. Before exiting the game, players will leave the room and enter a cityscape where a motivational video will be played along with hopeful comments. In doing so, players will be left with a touch of hope that can further help to alleviate their PTSD symptoms, as shown in Figure 4.

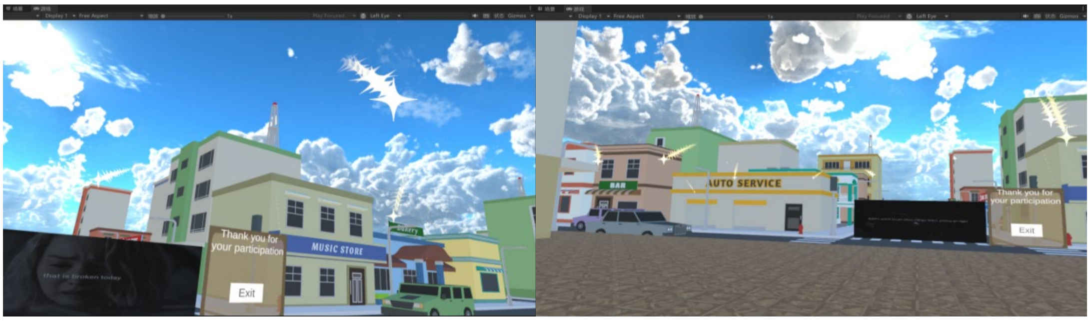

Figure 4: Final Integrated Cityscape Scene

4. Experimentation

4.1 Design

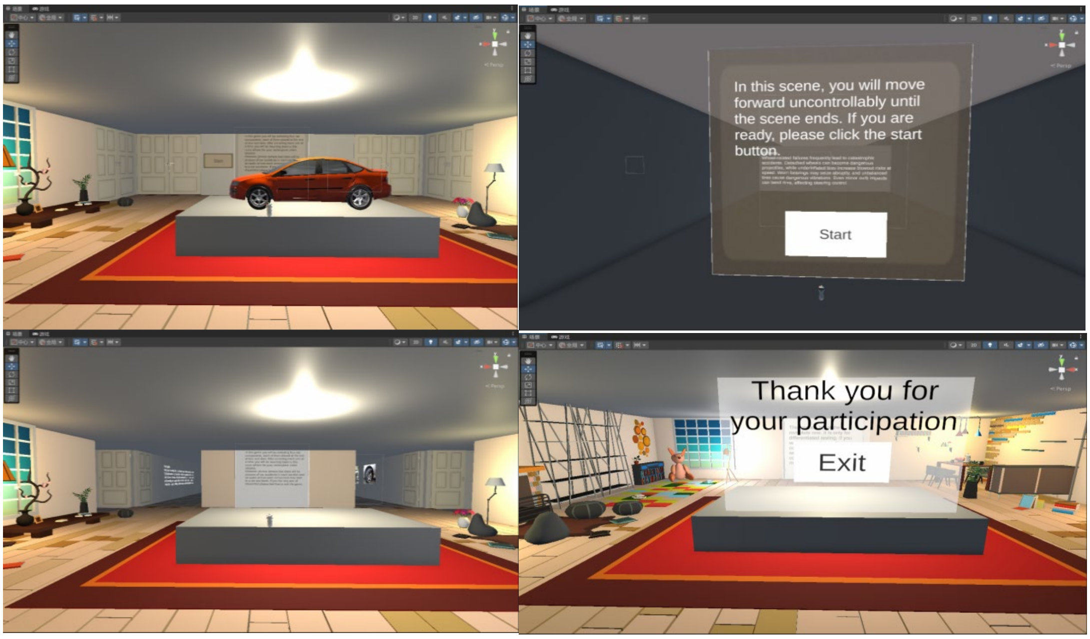

Figure 5: Differences among the Four Game Versions

To evaluate the therapeutic effectiveness of the MDA-based VR design, A controlled experiment was conducted consisting of one control group (full MDA version) and three variable groups, each lacking a specific MDA component. Specifically, version 1 lacks user control, where users are unable to control the speed and direction of movement. The mechanics are altered by disallowing user movement. The dynamics then imply a loss of gradual exposure where users cannot return to the safe zone after experiencing trauma-related triggers. The aesthetic goals of a controlled exposure and a constructed

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comfort zone are also reduced. Version 2 directly lacks gradual exposure, where each hall consists of multiple pictures instead of increasing linearly. From the mechanics layer, the reduction grants the user unrestricted access to every room yet challenges the dynamic and aesthetic goals of gradual experience and exposure. Version 3 reduces the resolution phase, a central mechanic of the game. From the dynamics layer, users are unable to experience a reflection stage. From an aesthetic perspective, the goal of imbuing hope and achievement will not be achieved, drifting from the original emotional purpose of this project, as shown in Figure 5.

4.2 Participants

A total of 14 volunteers, aged 18 to 40, participated in this experiment. Participants were healthy adults with no history of psychiatric or neurological disorders, including motion sickness. Gender distribution was approximately balanced. Participants were randomly assigned to each of the four experimental groups. 4 participants joined the control group, 4 joined version 1, 3 joined version 2, and 3 joined version 3. Before the experiment, all volunteers provided informed consent after receiving a full explanation of the project’s purpose and procedures. Participants can withdraw from the experiment at any point.

4.3 Procedure

Participants were briefed on how to use the VR equipment and the game's objective. They can also choose to test and familiarize themselves with the equipment before starting. Each participant played their assigned version of the game for approximately 10 to 15 minutes. Participants completed relevant tasks, such as finding and returning car components. In-game events, including unlocking doors, environment transitions, and triggered emotional evaluation, are displayed as short questions. Participants rate their current emotional state using a Subjective Units of Distress Scale (SUDS) from 0 (extremely distressed) to 4 (completely calm) and current safety level from 0 (very unsafe) to 4 (very safe). Immediately after completing their sessions, participants filled out a 13-item post-experiment questionnaire that targeted the more general conditions users feel after playing the game, including topics of control, safety, and anxiety. These questions are also rated using SUDS from 0 (extremely insecure) to 10 (completely safe), 0 (extremely inefficacious) to 10 (high levels of self-efficacy), 0 (extremely uncontrollable) to 10 (completely controllable), and 0 (completely calm) to 10 (extremely anxious).To enable in-depth analysis at the individual level, each participant's in-game questionnaire data is combined with their post-game questionnaire data. This linkage was achieved as follows: during the VR experience, the system automatically recorded a unique timestamp and participant ID for each in-game questionnaire response. In subsequent data processing, this ID and timestamp sequence is used to match all in-game reactions of a single participant with their corresponding post-game questionnaire responses. This method ensured that the complete emotional trajectory for each participant could be traced from the beginning to the end of the game.

5. Results

The heart rate heatmap in figure 6 reveals a clear physiological "exposure–recovery pattern." Bright bands mark periods of elevated heart rate coinciding with VR exposure phases, indicating stimulus-induced arousal. Subsequently, darker regions demonstrate a return to baseline heart rate during safe intervals, providing objective evidence of successful emotional self-regulation. This physiological recovery trajectory directly aligns with the subjective reports wherein participants' anxiety subsided after final exposure.

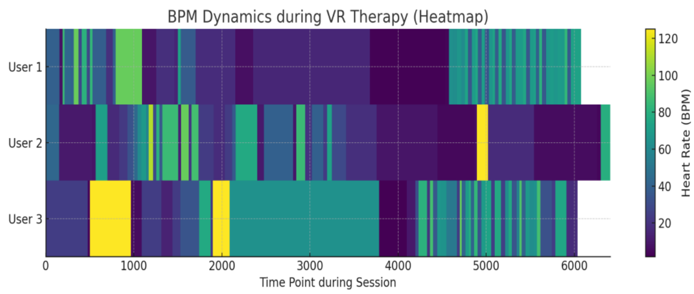

Figure 6: BPM Dynamic Heatmap

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The violin plots in figure 7 depicting BPM distributions offer statistical insights into participants' physiological stability. Narrow and concentrated distributions observed in the complete MDA group indicate uniform heart rate patterns and greater physiological stability. In contrast, broader or multi-peaked distributions in other groups suggest erratic stress responses and less effective regulation. These findings substantiate the role of the MDA framework in not only reducing psychological anxiety but also in promoting a more stable and controlled physiological state.

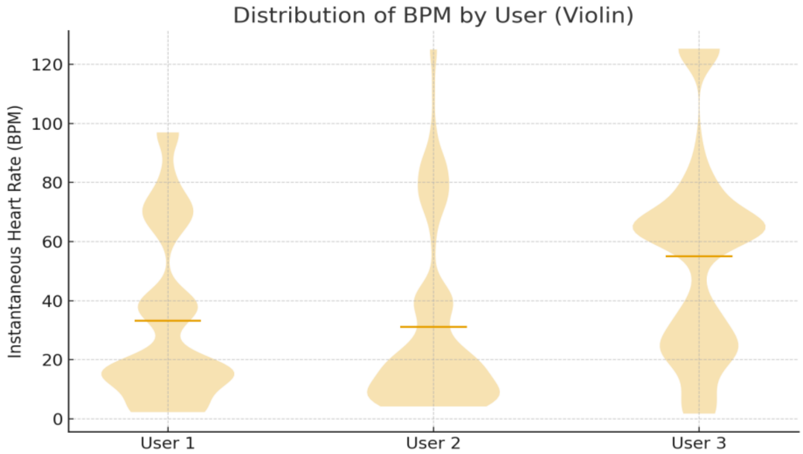

Figure 7: Violin Plot

The dual-axis time-series chart in figure 8, which synchronously displays infrared (IR) signal intensity and heart rate (BPM), confirms both data reliability and psychological engagement. The stability of the IR signal throughout the session attests to high-quality data acquisition. The coherent fluctuations in BPM, particularly the observable decrease during safe room intervals, confirm that the physiological changes were driven by the designed psychological experience. This validates the system's engineering goal of maintaining a controllable environment and demonstrates a direct alignment between the "safe room" game mechanic and intended therapeutic outcome of fostering calmness.

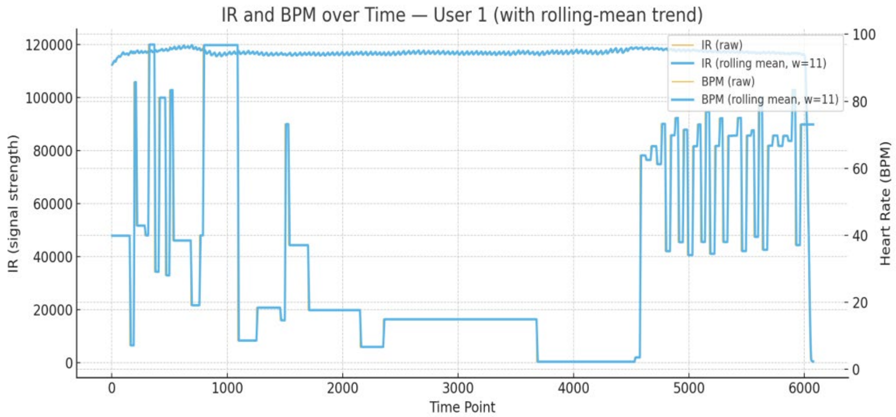

Figure 8: IR and BPM over Time

To gain a holistic understanding of the user experience, real-time, progress-oriented data from the in-game questionnaires was integrated with retrospective, general data from the post-game survey. This multi-faceted approach allows the analysis to paint a comprehensive picture of each participant’s emotional journey.

The analysis revealed a consistent and coherent pattern between the two data sources. Participants who reported lower levels of in-game "safety" and higher levels of in-game "anxiety" during the exposure halls consistently scored lower on the post-game "Safety" and "Self-Efficacy" scales and higher on the post-game "Tension" scale. Conversely, those who reported utilizing the safe room effectively to lower their in-game anxiety overwhelmingly provided positive feedback in the post-game questionnaire regarding their sense of control and ability to manage the experience.

A particularly telling finding emerged from tracing the emotional trajectory of individual participants. For a clear majority of users (12 out of 14), there is a recognizable "recovery pattern": their in-game

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anxiety scores peaked in the final exposure hall and then showed a marked decrease upon returning to the safe room. In their post-game responses, this same group of participants predominantly described the experience as "manageable" and reported a sense of "accomplishment," scoring highly on the "Self-Efficacy" dimension. This pattern was most pronounced and consistent among participants in the complete version of the game.

Figure 9 shows the results for the anxiety and safety measure questions. According to the chart, the complete version had the largest proportion of participants choosing “very calm.” On the other hand, the porportions for no-resolution, no-control, and no-gradual were all lower than the complete version, meaning that, in comparison, participants felt more anxious. The data imply that the elimination of any of the MDA elements led to increased anxiety, thus underscoring the importance of the MDA framework in providing a calm and peaceful experience for participants.

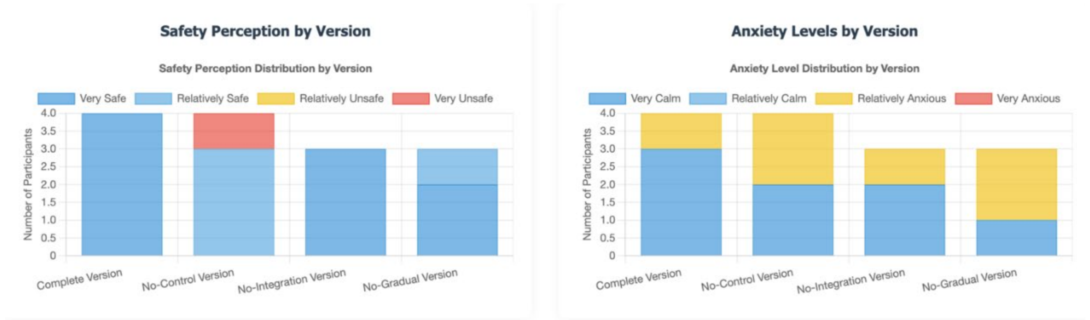

Figure 9: In-Game Data Analysis and Comparison

Figure 10 depicts the results of the after-game questionnaire, calculated and analyzed via SUDS. According to the graph, the complete version had a higher score of average safety, control, and self-efficacy, meaning that overall, the inclusion of all elements of the MDA framework ensured players a more relaxed and pleasant experience. Moreover, the complete version also had a lower score of tension in comparison to the other versions.

Figure 10: Statistical Data of the External Questionnaire

6. Discussion

After analyzing the data, it is concluded that all the features of the MDA framework are necessary to achieve full functionality. The data indicates that the “safe room” mechanic (mechanics) grants players the ability to pause the exposure process at any time (dynamics), which is considered the most critical factor in generating a 'sense of security' (aesthetics). This is the case where data for the no-controls’ safety and self-efficacy were low and anxiety measures were high, where players lacked access to this “safe room.” Furthermore, allowing players mobility (mechanics) and control of their own movements

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is directly proportional to both players' self-perception of control (self-efficacy), to safety levels, and to anxiety measures (dynamics & aesthetics), as evident in the comparison between values of no-control and complete "in-game anxiety measure" and "in-game safety measure" data. This implies that the elements of the MDA framework intertwine to manifest a safe and pleasant atmosphere for players. Additionally, data also support the claim that a resolution phase is beneficial in reducing anxiety, thus showing the importance of aesthetics (the atmosphere of hope and motivation) in alleviating anxiety or stress. Lastly, a gradual emotional experience (in terms of dynamics and aesthetics) is beneficial for both reducing anxiety and increasing safety perceptions, as data in the external questionnaire features the no-progressive results as demonstrating lower safety, control, self-efficacy, and calmness when compared to the complete version.

By precisely linking data through timestamps, this study ensured the reliability of the correspondence between in-game and post-game data, thereby providing a solid foundation for the conclusions regarding the effectiveness of the MDA framework.

Nevertheless, there are limitations to both the scope and accuracy of this experiment. The main limitation of this study is that the participants were a non-clinical sample, and the results cannot be directly generalized to the PTSD patient population. The primary aim of this study is to validate the system's design concept, feasibility, and user experience, laying the foundation for future clinical research. Additionally, due to the large number of data samples I have, the conclusion may inevitably contain inaccuracies. It is also challenging to ensure that participants in this experiment are unaware of which group they are in, whether the control or variable group, and thus do not influence the answers they provide to the given questions. Furthermore, the influence of my project is limited by the nature of VR itself, where normal families might not have the ability to purchase such hardware and thus will not be able to utilize VRET in PTSD treatment.

In the future, I aim to expand the volume of samples to achieve greater accuracy. I also aim to target more different triggers of PTSD, including war, sexual assault, and so on. In doing so, I would be able to expand the scope of this project and target a broader population, as RTA PTSD is only a small portion of many others.

This project adopts a novel perspective, distinct from traditional solutions for alleviating PTSD. Within communities and hospitals or even individual households, this project can influence a large number of PTSD patients, helping them cope with their trauma and fears. This study also demonstrates the importance of gamification elements and the MDA framework in VRET, providing insight for future VRET-based solutions in showing the necessity of such features.

7. Conclusions

Thanks to the aforementioned data linking method, it was possible to verify the consistency between in-game and post-game experiences at the individual level. The analysis revealed that the MDA framework has demonstrated its significance in the gamification of PTSD therapy. This study successfully developed and preliminarily validated a VR rehabilitation game prototype based on the MDA framework. The results indicate that the prototype system has good usability and can effectively guide users' emotional experiences, achieving controlled exposure and relaxation. This provides a strong design paradigm and preliminary evidence for future studies in the treatment of PTSD populations. Through this experiment and analysis of the collected data, this study has demonstrated that the elimination of any of these features results in increased anxiety and decreased functionality compared to the full version, which includes all of these features. The MDA framework and VRET combined are thus valuable and effective solutions for PTSD.

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