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Virtual reality for addressing aggression and psychophysiological responses in youth. Early evidence from a pilot study

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ABSTRACT

Conflict among socially vulnerable youth is a multifaceted phenomenon, with aggression and substance use representing components that carries profound psychological, social, and health consequences and thus constitutes a key target for clinical intervention. Traditional assessment and treatment approaches often face limitations in addressing the complexity of aggressive responses in ecologically valid contexts. Virtual reality (VR) offers a promising complementary tool for at-risk youth, providing immersive, controlled, and safe environments to evaluate and intervene in biopsychosocial processes underlying aggression. Thus, this pilot study aimed to explore and validate the use of VR to address aggression among youth. 54 participants included a nonclinical young adult group (NCYA, n = 42; age 19.69 ± 1.51 years) and a clinical adolescent group (CA, n = 12; 15.58 ± 0.99 years) and were exposed to three VR scenario involving emotional recognition, ambiguous social situations, and anger management challenge (referred as GINSO-VR). Psychological variables—including aggression (AQ, RPQ), anger state (STAXI-S), emotion regulation difficulties (DERS), drug consumption (AUDIT, CAST), emotional state (SAM) and behavior during GINSO-VR—as well as biological variables (EEG, heart rate variability and salivary cortisol, testosterone, and alpha-amylase) were assessed, together with VR presence questionnaires (PQ, MPS) and Simulator Sickness Questionnaire (SSQ). Results revealed statistically significant VR-related pre-post changes. Importantly, biological markers accounted for a substantial proportion of the variance in post-session anger state ($R^2 = 0.875$, $p < 0.001$) in the NCYA group and served as statistical mediators and moderators of the relationship between VR exposure and reactive/proactive aggression. These findings suggest that GINSO-VR can be a complementary tool for therapeutic interventions targeting aggression in this population.

1. Introduction

Aggressive behavior is a significant concern during adolescence due to both its high prevalence and its personal and social consequences (Kann et al., 2018). Recent studies indicate that a considerable proportion of adolescents engage in physical fights, with prevalence rates ranging from 17% (Henriksen et al., 2021) to 31.1% (Moore et al., 2014). This issue is particularly pronounced in clinical populations, especially among adolescents receiving inpatient psychiatric treatment, where substantially higher rates have been reported, reaching up to 87.1% (Asghari et al., 2021). Various mental health disorders—such as anxiety disorders (Chung et al., 2019), attention deficit disorders, borderline personality traits, and bipolar disorder (Aymerich et al., 2025)—have been associated with an increased presence of aggressive behavior during adolescence. Substance use has also been linked to higher levels of anger and physical aggression during this developmental stage (Vegas et al., 2024). Moreover, maladaptive aggression during childhood and adolescence has a detrimental impact on socio-emotional development. Specifically, reactive aggression—characterized by impulsive responses to perceived threats and experiences of anger—has been associated with negative affectivity, depressive and anxious symptoms, and difficulties in emotional self-regulation. In contrast, proactive aggression, characterized by its instrumental nature, has been linked to gang involvement, drug abuse, and persistent delinquent

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trajectories (Girard et al., 2019).

The factors contributing to the emergence of aggressive behavior form a complex and interconnected network that includes both individual characteristics (such as certain personality traits, negative emotional states, attitudes, and cognitive biases) and contextual elements, such as provocation, frustration, or the presence of incentives (Anderson & Bushman, 2002). These factors influence cognitive, emotional, and physiological processes, thereby shaping appraisals and decisions that may lead to aggressive responses (Allen & Anderson, 2017).

Various cognitive and emotional mechanisms have thus been identified as risk factors for the development of aggressive behavior. Among them, anger stands out as the emotional component of aggression (Spielberger & Reheiser, 2009). According to Anderson and Bushman (2002), anger can play multiple roles in triggering aggressive actions. On the one hand, it reduces inhibitory barriers to aggression by legitimizing retaliation and impairing processes such as moral reasoning. It also sustains aggressive intent by intensifying attention to and memory of provocative experiences. Furthermore, anger functions as an internal cue that guides causal attributions of others' behavior, fostering hostile interpretations in ambiguous situations. Finally, it increases physiological arousal, thereby facilitating the enactment of aggressive responses.

Another key factor in the emergence of aggressive behavior is the so-called hostile attribution bias (HAB). According to the Social Information Processing Model (Crick & Dodge, 1994), aggressive behavior is influenced by a series of cognitive errors in the processing of social information. Among these errors, HAB refers to a systematic tendency to interpret others' actions as intentionally hostile in ambiguous situations. Early experiences of negative socialization—such as physical abuse or the modeling of aggressive behaviors by significant figures—are considered foundational in the development of HAB (Dodge, 2006). This bias has been particularly associated with reactive aggression (Martinelli et al., 2018), functioning as a mediating mechanism between impulsivity, anger, and aggression in adolescents (Lin et al., 2024; Quan et al., 2022; Singh, 2020). In this context, interventions aimed at reducing HAB—typically involving training to generate benign interpretations of ambiguous social situations—have proven effective in decreasing aggression among youth. Greater effects have been observed on reactive aggression (Van Bockstaele et al., 2020), although benefits have also been reported for proactive aggression and anger (Vassilopoulos & Brouzos, 2022).

Difficulties in emotion recognition have also been associated with greater propensity for aggressive behavior. Specifically, research has shown that youth exhibiting aggressive behaviors tend to display a bias toward identifying anger and a reduced sensitivity to detecting sadness in others' emotional expressions (Clifford et al., 2021). In this regard, emotion recognition training programs aimed at modifying interpretative biases—by promoting the perception of happiness rather than anger in ambiguous facial expressions—have proven effective in reducing hostility, anger, and aggression among youth with violent behaviors (Li et al., 2023; Penton-Voak, 2013).

In addition to cognitive and emotional factors, numerous studies have emphasized the importance of physiological correlates in understanding aggressive behavior. At the psychophysiological level, heart rate (HR) and heart rate variability (HRV) are among the most frequently studied biomarkers, as indicators of autonomic nervous system activity (Aggensteiner et al., 2022). According to the model proposed by Raine et al. (1990), aggression may partly result from a lack of fear regarding the negative consequences of one's actions. In line with this perspective, several studies have found that both trait aggression and antisocial behavior across development are associated with lower resting HR (Jennings et al., 2019), as well as with reduced cardiac reactivity to stressful stimuli (Jennings et al., 2017), suggesting a general pattern of physiological hypoarousal. However, this relationship may be moderated by contextual and cultural factors.

HRV has been studied as a more precise indicator of autonomic nervous system functioning and the cardiovascular system's ability to adapt to environmental stimuli (Puhalla et al., 2020). In this regard, lower HRV in response to stressors has been associated with greater hostility and aggression, suggesting a pattern of reduced autonomic flexibility (Puhalla et al., 2020). In fact, profiles of "hot-blooded" (reactive aggression) versus "cold-blooded" (proactive) have been proposed based on physiological evidence (Fanti et al., 2024). However, recent evidence nuances these findings, as a meta-analysis did not find low HRV to be a robust predictor of reactive aggression (McCurry et al., 2024). These mixed results suggest that both heart rate and HRV may not serve as universally generalizable biomarkers but can contribute to understanding the multifactorial nature of aggression.

While HR and HRV reflect peripheral physiological processes, electroencephalographic (EEG) recordings allow for the direct examination of central nervous system activity associated with aggression. Recent resting-state EEG studies have provided valuable insights into the neurophysiological correlates of aggressive behavior during adolescence. However, findings suggest that these associations may vary depending on sex and the type of aggression. Niv et al. (2018) found that both increased frontal alpha activity and increased frontal beta activity predicted higher levels of aggressive behavior in adolescents; however, this pattern was observed only in males. Complementarily, Aggensteiner et al. (2022) observed that adolescents with disruptive behavior disorders showed lower alpha activity relative to a control group. Moreover, their results indicated that increased theta activity and decreased alpha activity were generally associated with aggression, while increased delta activity and reduced beta activity specifically predicted proactive aggression. Plus, beta power correlated negatively with proactive aggression among the clinical group (Aggensteiner et al., 2022). These findings suggest that distinct EEG frequency bands may be differentially involved depending on the type and context of aggressive behavior.

Frontal cortical asymmetry has also been a focus of interest in the study of the neurophysiological mechanisms underlying aggression. Several studies have indicated that a pattern of relatively greater activity in the left frontal hemisphere (i.e., lower alpha power in the left hemisphere compared to the right) is associated with higher levels of aggression (Peterson et al., 2008). This finding aligns with the approach–withdrawal model, which posits that anger and aggression are linked to an approach-related motivational system, characterized by increased anterior left cortical activation (Coan & Allen, 2004).

In line with this, Keune et al. (2012) observed a pattern of greater alpha activity in the right hemisphere compared to the left among incarcerated violent offenders, with this pattern being extreme in one-third of the cases. However, subsequent findings by Keune et al. (2018) did not replicate this association in a similar sample, as they found no significant relationships between frontal alpha asymmetry and aggression. Nevertheless, they did find that the trait of callous-unemotionality was associated with relatively greater right hemispheric activation—namely, a pattern associated with withdrawal-related processes. This neurophysiological profile of emotional detachment may represent an underlying mechanism for proactive aggression, supporting the need to distinguish between reactive and proactive forms of aggression.

A third available and useful source for psychophysiological studies of aggression is the study of salivary hormones. Although the general finding is that salivary testosterone and cortisol correlates positively with aggressive behavior in young population, a recent review concluded that there is a rather complex interaction between these two, which is also modulated by age and sex (Cima et al., 2025; Ren et al., 2020). Another relevant hormone representative of the sympathetic nervous system activation is alpha-amylase, in which a low reactivity was related to higher antisocial behavior (Susman et al., 2010) or autonomic dysregulation after exposure to community violence (Hasson et al., 2022).

Importantly, understanding the underlying neurobiological mechanisms of aggression can improve the effectiveness of usual therapies

(Matthys & Schutter, 2021). At this point, various therapeutic approaches have demonstrated differing levels of effectiveness in managing aggression among youth and its physiological correlates. Cognitive Behavioral Therapy (CBT) has consistent evidence supporting its role in reducing aggressive behaviors, enhancing social skills, and improving anger management (Chen et al., 2014; Liu et al., 2025; Smeets et al., 2015). Consequently, interventions targeting anger management—particularly those incorporating cognitive-behavioral components and multimodal approaches, such as the Aggression Replacement Training program (ART, Glick & Gibbs, 2010)—have shown effectiveness in reducing aggression among adolescents, yielding positive outcomes in anger control, social functioning, and moral reasoning (Ensafdaran et al., 2019). Complementary, not only HRV (Sukhodolsky et al., 2016), EEG (Wang et al., 2020) and hormonal (Schoorl et al., 2017) information can help to identify individuals who benefit from intervention for aggression, supporting a neuroscience-based classification system to improve treatment outcomes in aggressive youth, but also can be a direct target of intervention to reduce aggression through new noninvasive techniques such as high definition tDCS (Sergiou et al., 2023) or biofeedback (Hillman, 2025; Molina-Cantero et al., 2025).

All these biobehavioral variables can be moderated by sex. For instance, one study found that the association between low HR and aggression was observed only among males (Portnoy et al., 2020). On the other hand, a high alpha-amylase reactivity was found in girls following peer victimization and related to heightened frustration and aggression (Rudolph et al., 2010). Interestingly, in a sample of control females without psychiatric nor criminal history, enhancing relative left frontal activity through transcranial direct current stimulation (tDCS) led to anger-induced aggression (Hortensius et al., 2012). These findings support a multifaceted therapeutic strategy to address the complex nature of aggression.

More recently, the effectiveness of virtual reality (VR) in reducing aggression among the young population has been increasingly supported by empirical evidence. A recent study shows that brief VR-based relaxation sessions led to clear reductions in aggression and emotional distress among at-risk adolescents, with effects emerging after just two weeks and strengthening by week four (Sabo-Brants et al., 2026). These participants also experienced consistent boosts in positive mood and flow immediately after each session, suggesting meaningful short-term emotional benefits (Sabo-Brants et al., 2026). Another research shows that a brief virtual-reality intervention (ImpactVR), significantly reduced callous-unemotional traits, conduct problems, and reactive aggression in youth with conduct disorder (Thomson et al., 2025). These improvements were observed across caregiver and self-reports, highlighting the potential of immersive, emotion-focused training to produce meaningful socioemotional change (Thomson et al., 2025). In this sense, another approach consisted in a multicenter randomized controlled trial in which CBT combined with VR is more effective in reducing aggressive behavior in children compared to care-as-usual and CBT using roleplays (Alsem et al., 2023). Another recent study also showed that CBT supported by VR reduced significantly predisposition to delinquency related to child-to-parent violence (Palanques et al., 2025). A comprehensive meta-analysis of VR interventions targeting aggression further reinforced these findings, reporting statistically significant reductions in observer-reported aggression ($g = -0.27$; $p = 0.029$), self-reported aggression ($g = -0.47$; $p < 0.001$), anger ($g = -0.74$; $p = 0.005$), and impulsiveness ($g = -0.47$; $p < 0.001$; Roncero et al., 2025). Although a few studies included women or mixed samples, none of the included studies in this meta-analysis conducted gender-specific analyses or reported differential outcomes by sex. As a result, there is insufficient empirical data to determine whether VR interventions are equally effective. These results collectively suggest that, in general, VR represents a promising modality for aggression management in youth.

The psychological mechanisms underlying the effectiveness of VR in this context appear to involve increased emotional engagement, immersive learning experiences, and greater appreciation for the therapeutic process (Alsem et al., 2023). These elements likely enhance the efficacy of behavioral interventions delivered through VR. Moreover, VR environments have been identified as effective platforms for anger management training, offering participants realistic simulations in which they can practice and refine their emotional regulation strategies (Palanques et al., 2025). Ethical considerations are central to the application of VR in interventions aimed at aggression reduction, particularly among vulnerable or high-risk populations. For example, VR-based interventions have been explored in populations with complex psychiatric profiles, such as youth with schizophrenia, yielding reductions in anger, improvements in conflict resolution skills, and lower levels of aggressive behavior (Dellazizzo et al., 2019). Additionally, a study investigating the acceptability and feasibility of the Virtual Reality Aggression Prevention Treatment (VRAPT) in prison settings found the intervention to be generally well-received by both participants and therapists, underscoring the importance of ethical oversight and adaptability in the deployment of VR interventions in sensitive environments (Tuente et al., 2020; Woicik et al., 2023).

Despite these promising findings, there are several limitations associated with the use of VR to mitigate aggression in young populations. The diversity of VR intervention protocols and the variability in study samples need further research to determine best practices and optimize therapeutic outcomes (Roncero et al., 2025).

The system that leads to aggression in youth is rather complex and involves several key variables, including environmental and biological factors as well as the interaction between them (Baskin-Sommers et al., 2024). In fact, taking into account biological information can help to improve psychological interventions in this population (Fernández-Moreno et al., 2024).

Emerging evidence also points to potential neurobiological effects of VR interventions on aggression. For instance, the use of embodied perspective-taking in VR has been explored as a mechanism to reduce violent behaviors, including intimate partner violence, by targeting affective and behavioral pathways linked to aggression (Johnston et al., 2023). The integration of VR in anger management training programs likewise supports its potential role in modulating neurological and physiological responses associated with aggressive impulses (Jo et al., 2022). In fact, a combined intervention with VR (AMVR-CBTP) reduced anger and normalized abnormal EEG signal in destructive and impulse-control disorder patients (Ryu et al., 2016). These findings suggest that beyond behavioral change, VR may influence underlying neural mechanisms involved in aggression regulation.

Our main goal was to explore the effects of the VR protocol on relevant psychological and physiological measures in order to validate the instrument for intervention in aggression reduction of young individuals. Specifically, we aim to validate the VR scenarios developed for the assessment of facial emotion recognition, exposure to ambiguous situations, and anger control in response to an explicit situation. For this purpose, we assessed the psychological and behavioral reaction to these VR tasks in both control and clinical groups of young participants. Additionally, physiological parameters previous, during and after the situation in VR were analyzed, only in the young adult control group, due to practical limitations of material accessibility and transportation for the clinical group in the residential center. With all this, we aim to examine the differences between the pre- and post-VR sessions, as well as between the control and clinical groups, together with the normative scores in VR tasks and the relationship between psychological and physiological variables. Finally, a specific aim was to find relevant biological markers of anger state after the VR situation. Thus, we hypothesized that the VR scenarios would elicit measurable psychological, behavioral, and physiological responses, supporting their validity as tools for the assessment of social conflict–related processes. Specifically, we expected that participants in the clinical group would show greater difficulties in emotion recognition, a stronger tendency toward hostile interpretations of ambiguous situations, and poorer anger regulation compared to the control group. We also hypothesized that exposure to the VR scenarios would produce changes between pre- and post-session psychological measures and would induce physiological activation during the VR tasks. Finally, we expected significant associations between psychological responses and physiological parameters, potentially identifying biological markers related to anger state following the VR situation.

2. Materials and methods

2.1. Participants

The total sample was 54 young participants divided into the nonclinical young adult group (NCYA, n = 42) and the clinical adolescent group (CA, n = 12). The NCYA group consisted of 42 young volunteers (20 females, 21 males, 1 that identified as "other"; 88% university students); mean age 19.69 ± 1.51 years and range 18-24. The sample for the clinical group (CA) was taken from the Residential Therapeutic Center for Adolescent Mental Health RECURRA-GINSO (Madrid) and comprised 12 teenagers (8 females, 4 males); mean age 15.58 ± 0.99 years. All of whom agreed to participate in the study and provided their written consent to participate between April and July 2025 (See Supplementary Material). In the case of the clinical group, informed consent was obtained from both the participants and the director of the residential center, who held legal custody, as the minors were under the guardianship of the child welfare authorities. Volunteers were excluded if they were diagnosed of any mental disorder the previous 6 months or consumed prescription drugs affecting the central nervous system (mainly anxiolytics and antidepressants). If any participant reported nausea, dizziness, or blurred vision during the VR session, the session would be stopped and the participant excluded from the study.

All the procedures in this study received approval from the ethics committee of University of Francisco de Vitoria (code 48/2024) and were in compliance with the Ethical Principles for Medical Research Involving Human Subjects as outlined in the Declaration of Helsinki by the World Medical Association (64th WMA General Assembly, Fortaleza, Brazil, October 2013), Recommendation No. R (97) 5 of the Committee of Ministers to Member States on the Protection of Medical Data (1997), and the Spanish Data Protection Act (Organic Law 15/1999 on the Protection of Personal Data, LOPD).

2.2. Measures

The study incorporated a range of psychological, behavioral, and physiological measures. Self-report instruments included drug screening via the Alcohol Use Disorder Identification (AUDIT, Spanish adaptation, Contel-Guillamon et al., 1999; Motos-Sellés, Cortés-Tomás, & Giménez-Costa, 2020) and the Cannabis Abuse Screening Test (CAST, Legleye et al., 2007; Rial et al., 2022). Emotional regulation and related processes were evaluated using the Difficulties in Emotion Regulation Scale (DERS, Spanish adaptation: Hervas & Jódar, 2008), which covers dimensions such as emotional rejection, dysregulation, interference, neglect, and confusion. Anger was assessed via the STAXI (Spielberg, 1999; Miguel-Tobal et al., 2009), considering both trait and state components (the latter pre- and post VR session). Aggressive tendencies were measured using the RPQ (proactive and reactive aggression) (Rodríguez et al., 2006) and the AQ (physical, verbal, anger, and hostility) (Spanish adaptation, Rodríguez et al., 2002). Impulsivity was examined through the BIS-11 (Spanish adaptation, Martínez-Loredo et al., 2015; Oquendo et al., 2001), covering cognitive, motor, and non-planning dimensions. The hostile attribution bias was measured by the items of the Hostility Questionnaire (HO) (Barefoot et al., 1989; mexican adaptation, Martínez-Mir, 2022). The Self-Assessment Manikin (SAM) (Bradley & Lang, 1994) for emotional valence, arousal, and dominance (pre/post). After the VR session, presence was evaluated using Presence Questionnaire (PQ; Witmer & Singer, 1998) and Multi-modal Presence Scale (MPS; Makransky et al., 2017), and potential related sickness was assessed with Simulator Sickness Questionnaire (SSQ; Stanney et al., 1997).

Behavioral measures included accuracy of emotional recognition (correct/incorrect responses), response times, and video-coded behavior (frequency, duration, and latency via RatonTime, Moreno-Fernández et al., 2023). Physiological data included heart, brain and hormonal measures pre, during and after the VR session. With polar bands H10, we measured heart rate (bpm), heart rate variability (RMSSD, SDNN) and respiration estimates by Kubios software. A commercial headband for electroencephalogram was used to register delta, theta, alpha and beta bands of four dry electrodes distributed in the frontal (AF7 and AF8) and temporal-parietal (TP9 and TP10) according to 10–20 system of electrode placement (Muse-2 equipment, Mind Monitor app for extracting relative power of alpha, beta, theta y delta bands). Salivettes (Sarstedt®) were used for saliva collection, and biomarkers (cortisol, testosterone, and alpha-amylase) were analyzed using ELISA according to the manufacturer's instructions (Salimetrics® kits 1-3002, 1-2402 and 1-1902, respectively; BioNOVA científica S.L., Madrid, Spain).

2.3. VR sessions procedure

Data for the present study was obtained in single sessions, the protocol followed is represented in Fig. 1. For the NCYA group, subjects were invited to participate via snowball sampling at the campuses of Universidad Francisco Vitoria and Autonomous University of Madrid and provided informed written consent and completed the psychological questionnaires mentioned above beforehand through Qualtrics platform. In the case of the clinical sample, convenience sampling was carried out in those who had met the criteria and these questionnaires were filled out on paper the same day under professional supervision.

During the session, the participants were informed about the scope of the study and written informed consent was obtained (Supplementary Material). First, the participants completed the following questionnaires: the STAXI-2 (state version), the Self-Assessment Manikin (SAM) to assess valence, activation, and control, and three additional questions concerning craving, weekly physical activity, and previous experience with VR.

For the NCYA group, physiological sensors were placed: a saliva sample was collected for the basal measure (t1), a Polar H10 chest strap for heart rate (HR) and a Muse-2 headband for brain activity (EEG). A baseline measurement of both signals was recorded during a 5-min resting-state period, with their eyes open with a fixation dot on the wall 90 cm away (Sampedro-Piquero et al., 2024).

The VR equipment consisted of PICO 4 Ultra Enterprise headset connected to a Tablet (Samsung Galaxy s6). The software GINSO-VR, developed by Innovae Group (Spain), consisted of four scenarios related to emotion recognition, ambiguous situations, and anger management (See video for more details: VR extract.mp4; procedure in Fig. 1). The VR scenarios were transmitted from a tablet to the VR headset under the supervision of the researcher. These included a tutorial lasting approximately 2 min in which participants learned how to move around the available space (approximately 30 m^2) and pick up objects using the controller button. Then, a block of four tasks related to facial emotion was performed, which is represented throughout the manuscript as VR1. First, an emotional recognition task in which a total of 10 faces expressing different emotions appeared at the participant's eye level with four answer choices (anger, sadness, fear, and joy).

Then, an easy emotional discrimination task was performed in which the participant is surrounded by 10 young full-body avatars and must identify and select the one that expresses the emotion displayed as text on the screen (again, four different facial emotions: anger, sadness, fear, and joy). Finally, two highly difficult emotional discrimination tasks were conducted to the participants who had to identify again one specific emotion in all 10 avatars, but this time emotional facial expression was more subtle. VR1 concluded with a total of 40 responses and had a

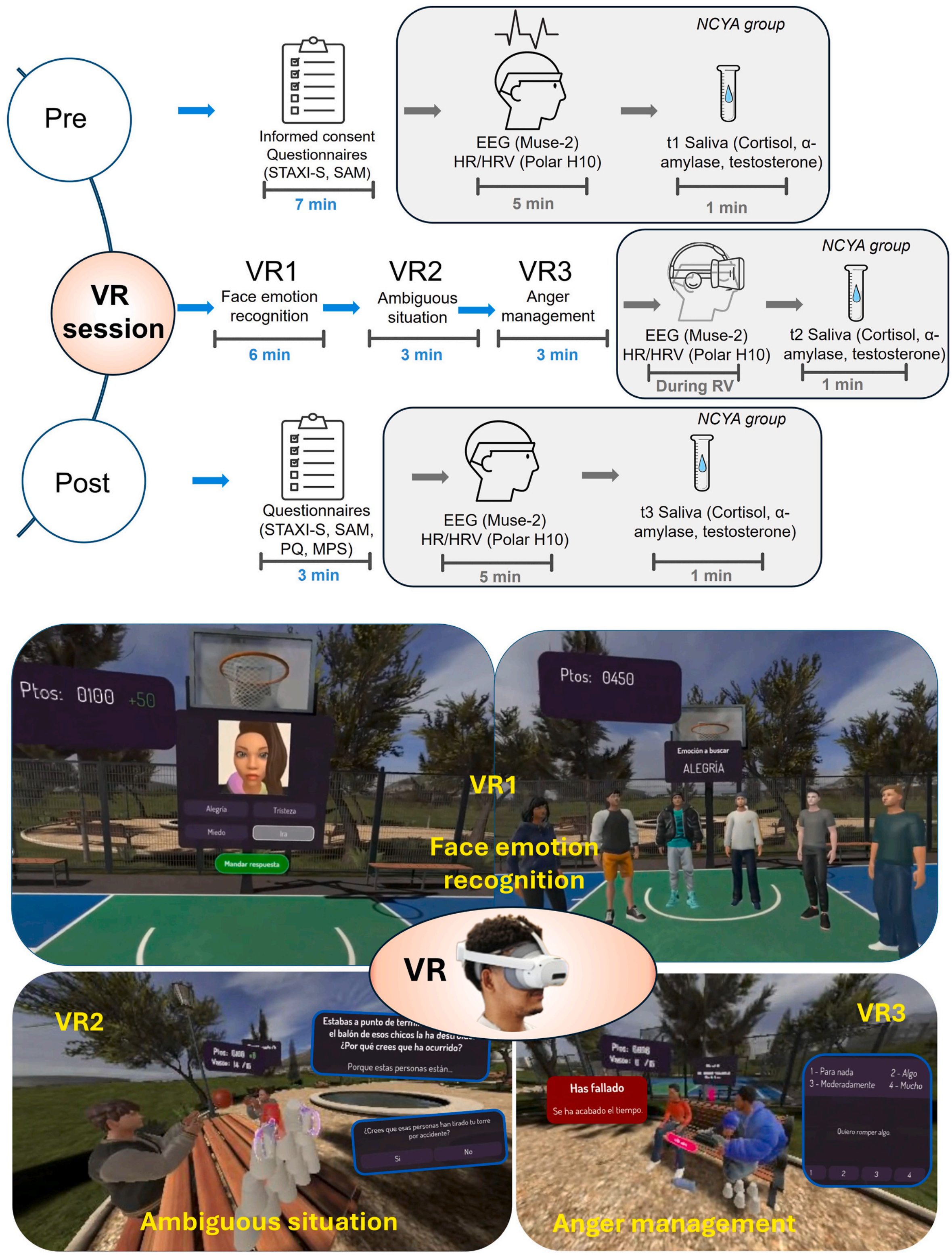

Fig. 1. Protocol for VR sessions (GINSO-VR). Abbreviations: HR, heart rate; HRV, heart rate variability; EEG, electroencephalogram; VR, virtual reality. Video extract on the following link: https://n9.cl/abnbq.

total duration of approximately 6 min. After VR1, the VR session proceeded with an *ambiguous provocation task* (VR2, approximately 3 min) which involved a cup-stacking activity. Just as the participant was about to complete the task, two avatars knocked over the cup tower with a basketball (see video), while their intentions remained unclear. This was followed by a *anger management task* (VR3, approximately 3 min), which also involved a cup-stacking activity. During this task, the participant ran out of cups and had to request additional ones from two avatars seated on a bench. Rather than providing the cups, the avatars responded with verbal insults and provocative behavior for exactly one and a half minutes. VR3 concluded with a second administration of the STAXI-2 by the VR environment (Fig. 1).

Throughout the VR experience in the NCYA group, continuous brain and heart rate (HR) activity were registered by EEG and Polar Sensor respectively, and event markers were inserted at the beginning and end of each task. Following the VR, a second saliva sample was collected (t2). Participants then completed questionnaires related to the VR experience: the Simulator Sickness Questionnaire (SSQ), Presence Questionnaire (PQ), Multi-modal Presence Scale (MPS), and the SAM scale again. A second 5-min resting-state recording of EEG and HR was obtained, and finally, a third saliva sample was collected (t3). A total duration of 1 h was required for this protocol of individual VR sessions.

2.4. Data analysis

To address the main objective of this pilot study, descriptive and frequency analyses were conducted. After testing the sample normality using Saphiro-Wilks' W test, given the small size of the sample (n = 54), it was determined to use nonparametric statistics (Wilcoxon matched pairs test, Friedman ANOVA, Spearman rank R, and Mann-Whitney U), since the data failed to follow normality ($p < 0.05$). To assess the group and sex differences, Wilcoxon matched pairs tests were conducted to compare by control or clinical groups, and men or women. Correlations were performed to see the relationship between biological and psychological variables, as well as with the anger state post (STAXI). Regarding the latter, multiple linear regression (backward stepwise) was also carried out in order to address the weight of the influence of the biological parameters. We used backward stepwise regression because the number of biological predictors was relatively large in relation to the sample size.

Table 1
Mean ± SEM values of the psychological and behavioral variables.

		Nonclinical young adult group (NCYA)			Clinical adolescent group (CA)			*NCYAV.CA*
		Girls n = 20	Boys n = 21	*All n=42*	Girls n = 8	Boys n = 4	*All n=12*	
Age		19.50 ± 0.31	19.81 ± 0.36	*19.69 ± 0.23*	15.38 ± 0.38	16.00 ± 0.41	*15.58 ± 0.29*	↓↓↓
AUDIT		3.80 ± 0.68	4.38 ± 0.73	*4.02 ± 0.49*	7.38 ± 2.80	8.50 ± 4.97	*7.75 ± 2.36*	=
CAST		0.35 ± 0.22	0.29 ± 0.17	*0.31 ± 0.13*	9.75 ± 3.67	12.75 ± 4.82	*10.75 ± 2.83*	↑
AQ		68.70 ± 3.84	64.76 ± 3.43	*66.79 ± 2.50*	96.25 ± 6.26	98.75 ± 5.68	*97.08 ± 4.44*	↑↑↑
Physical aggression		13.30 ± 0.95	15.86 ± 1.28	*14.60 ± 0.80*	26.88 ± 3.15	29.00 ± 2.27	*27.58 ± 2.19*	↑
Verbal aggression		13.70 ± 0.93	12.86 ± 0.83	*13.17 ± 0.61*	17.13 ± 1.92	16.00 ± 1.00	*16.75 ± 1.30*	=
Anger		16.30 ± 1.07	13.14 ± 0.93	*14.67 ± 0.72*	20.00 ± 1.45	21.25 ± 1.55	*20.42 ± 1.07*	↑
Hostility		18.50 ± 1.21	16.05 ± 0.92	*17.41 ± 0.77*	20.88 ± 1.93	21.00 ± 3.03	*20.92 ± 1.55*	↑
HO *Hostile attribution*		36.90 ± 1.82	36.10 ± 2.23	*36.57 ± 1.40*	37.75 ± 2.73	36.75 ± 0.75	*37.42 ± 1.80*	=
RPQ proactive		1.30 ± 0.38	2.38 ± 0.58	*1.86 ± 0.35*	7.25 ± 1.58	8.75 ± 1.80	*7.75 ± 1.18*	↑↑↑
RPQ reactive		7.10 ± 0.68	7.57 ± 0.77	*7.38 ± 0.50*	15.25 ± 1.03	13.50 ± 1.19	*14.67 ± 0.80*	↑↑↑
STAXI-Trait		22.45 ± 1.16	18.10 ± 1.12	*20.24 ± 0.85*	28.38 ± 3.48	24.75 ± 2.17	*27.17 ± 2.41*	↑
STAXI-State	***pre***	17.30 ± 0.83	17.33 ± 1.11	*17.31 ± 0.68*	20.88 ± 2.42	17.25 ± 2.25	19.67 ± 1.79	=
	post	19.72 ± 1.14	23.95 ± 1.95	*22.21 ± 1.19*	24.88 ± 3.69	31.00 ± 4.95	*26.92 ± 2.96*	=
	change	2.28 ± 1.45	7.00 ± 1.48	*5.03 ± 1.10*	4.00 ± 2.78	13.75 ± 6.33	*7.25 ± 2.97*	↑
Self-Assessment Manikin (SAM)								
Valence	***pre***	6.45 ± 0.38	6.29 ± 0.35	*6.38 ± 0.25*	5.63 ± 0.84	6.50 ± 0.96	*5.92 ± 0.63*	=
	post	6.10 ± 0.37	6.10 ± 0.38	*6.12 ± 0.26*	6.63 ± 0.73	5.25 ± 0.25	*6.17 ± 0.52*	=
Activation	***pre***	5.60 ± 0.52	5.29 ± 0.53	*5.43 ± 0.36*	6.13 ± 0.93	5.50 ± 0.96	*5.92 ± 0.68*	=
	post	6.25 ± 0.49	6.48 ± 0.39	*6.41 ± 0.30*	5.88 ± 1.11	6.50 ± 0.87	*6.08 ± 0.77*	=
Control	***pre***	6.35 ± 0.40	7.00 ± 0.32	*6.69 ± 0.25*	6.38 ± 0.94	8.00 ± 0.41	*6.92 ± 0.67*	=
	post	6.05 ± 0.44	6.67 ± 0.36	*6.26 ± 0.30*	6.63 ± 0.82	5.75 ± 1.80	*6.33 ± 0.77*	=
VR1 (face emotion recognition task)								
% accuracy easy task		78.00 ± 3.29	78.10 ± 3.76	*78.33 ± 2.43*	74.38 ± 6.43	75.75 ± 4.67	*74.83 ± 4.42*	↓
% accuracy difficult task		75.80 ± 4.00	77.49 ± 3.83	*76.70 ± 2.69*	70.81 ± 7.46	50.25 ± 11.88	*63.96 ± 6.70*	↓↓
Time easy task (seconds)		101.40 ± 6.91	89.86 ± 5.37	*95.64 ± 4.29*	98.63 ± 6.69	94.13 ± 6.63	*97.13 ± 4.83*	=
Time hard task (seconds)		104.24 ± 8.06	96.54 ± 5.06	*100.14 ± 4.62*	100.69 ± 7.67	93.50 ± 6.60	*98.29 ± 5.48*	=
VR3 (behavior during anger situation)								
Frequency throw/hit		0.00 ± 0.00	0.53 ± 0.28	*0.25 ± 0.14*	0.50 ± 0.3	0.75 ± 0.75	*0.58 ± 0.31*	=
Latency throw/hit		0.00 ± 0.00	11.74 ± 6.13	*5.42 ± 2.94*	1.48 ± .0.97	16.83 ± 16.83	*6.59 ± 5.56*	=
Time looking at avatars		56.83 ± 5.32	54.83 ± 3.43	*55.92 ± 3.12*	85.18 ± 4.47	89.11 ± 2.55	*87.80 ± 2.21*	↑↑↑
VR experience report								
Presence (PQ)		27.80 ± 0.94	29.62 ± 0.79	*28.52 ± 0.64*	25.25 ± 1.42	23.00 ± 1.47	*24.50 ± 1.08*	↓
MPS Physical		19.60 ± 1.09	18.76 ± 0.67	*19.19 ± 0.61*	18.25 ± 2.34	17.50 ± 1.71	*18.00 ± 1.61*	=
MPS Social		12.65 ± 1.07	12.48 ± 0.95	*12.64 ± 0.69*	13.00 ± 2.56	14.25 ± 3.15	*13.42 ± 1.93*	=
MPS Self-presence		16.60 ± 1.17	16.29 ± 0.88	*16.43 ± 0.70*	16.13 ± 2.59	15.25 ± 2.10	*15.83 ± 1.80*	=
Simulator Sickness (SSQ)		51.77 ± 4.71	30.29 ± 3.43	*41.76 ± 4.69*	-	-	-	
- Nausea (0-95.4)		32.13 ± 3.11	25.76 ± 2.59	*29.07 ± 3.10*	-	-	-	
- Oculomotor (0-83.38)		48.27 ± 5.16	26.53 ± 3.34	*38.08 ± 4.76*	-	-	-	
- Disorientation (0–89.76)		57.15 ± 6.83	26.45 ± 4.12	*43.09 ± 6.47*	-	-	-	

Statistically significant differences between groups (Mann-Whitney U) are represented as ↑ when the clinical adolescent group values are higher than the nonclinical young adult group, and ↓ when lower. ↑ $p < 0.05$; ↑↑ $p < 0.01$; ↑↑↑ $p < 0.001$; ↓ $p < 0.05$; ↓↓ $p < 0.01$; ↓↓↓ $p < 0.001$.

All statistical analyses were carried out using IBM SPSS version 23 (IBM SPSS Statistics, Corporate headquarters, New Orchard Road, Armonk, New York 10504-1722, USA) and the PROCESS macro for mediation analysis (Hayes, 2013).

3. Results

Table 1 displays the comparison between the control group and the clinical group across the different psychological and behavioral variables before, during and after GINSO-VR. Before the exposure, the clinical group displayed higher levels of aggression scores in AQ (Mann-Whitney $U = 89$, $p < 0.001$), both RPQ reactive ($U = 25$, $p < 0.001$) and proactive aggression ($U = 49$, $p < 0.001$), anger trait (STAXI-T, $U = 123$, $p < 0.01$) and cannabis consumption (CAST; $U = 99$, $p < 0.001$). Internal consistency (Cronbach's α) of questionnaires was either good ($\alpha \geq 0.80$) or excellent ($\alpha \geq 0.90$) for the majority of the tests: AUDIT ($\alpha = 0.81$), CAST ($\alpha = 0.98$), DERS ($\alpha = 0.94$), STAXI-T ($\alpha = 0.91$), RPQ ($\alpha = 0.91$), AQ ($\alpha = 0.87$), BIS-11 ($\alpha = 0.84$), HO ($\alpha = 0.79$), STAXI-S pre ($\alpha = 0.89$), STAXI-S post ($\alpha = 0.93$), SSQ ($\alpha = 0.78$), and MPS ($\alpha = 0.91$). However, the reliability was poor for the PQ ($\alpha = 0.58$).

A significant increase was found in both groups in self-reported levels of state of anger (STAXI-S) after exposure to the VR environments as compared to the basal state, being the change in the state score higher in the clinical group. The Wilcoxon test indicated statistically significant differences in the STAXI-S ($W = 3.744$; $p = 0.0002$), and when compared by sex, both groups displayed significant differences before and after exposure (males $W = 3.527$, $p = 0.0004$; females $W = 1.978$, $p = 0.048$); although statistical significance was higher in males. Interestingly, only in the clinical group there was a tendency towards statistical significance in the correlation among consumption of cannabis and Post levels of STAXI-S ($r = 0.51$; $p = 0.09$). Also, the clinical group spent more seconds looking at avatars in the anger situation ($U = 13$, $p < 0.001$) and

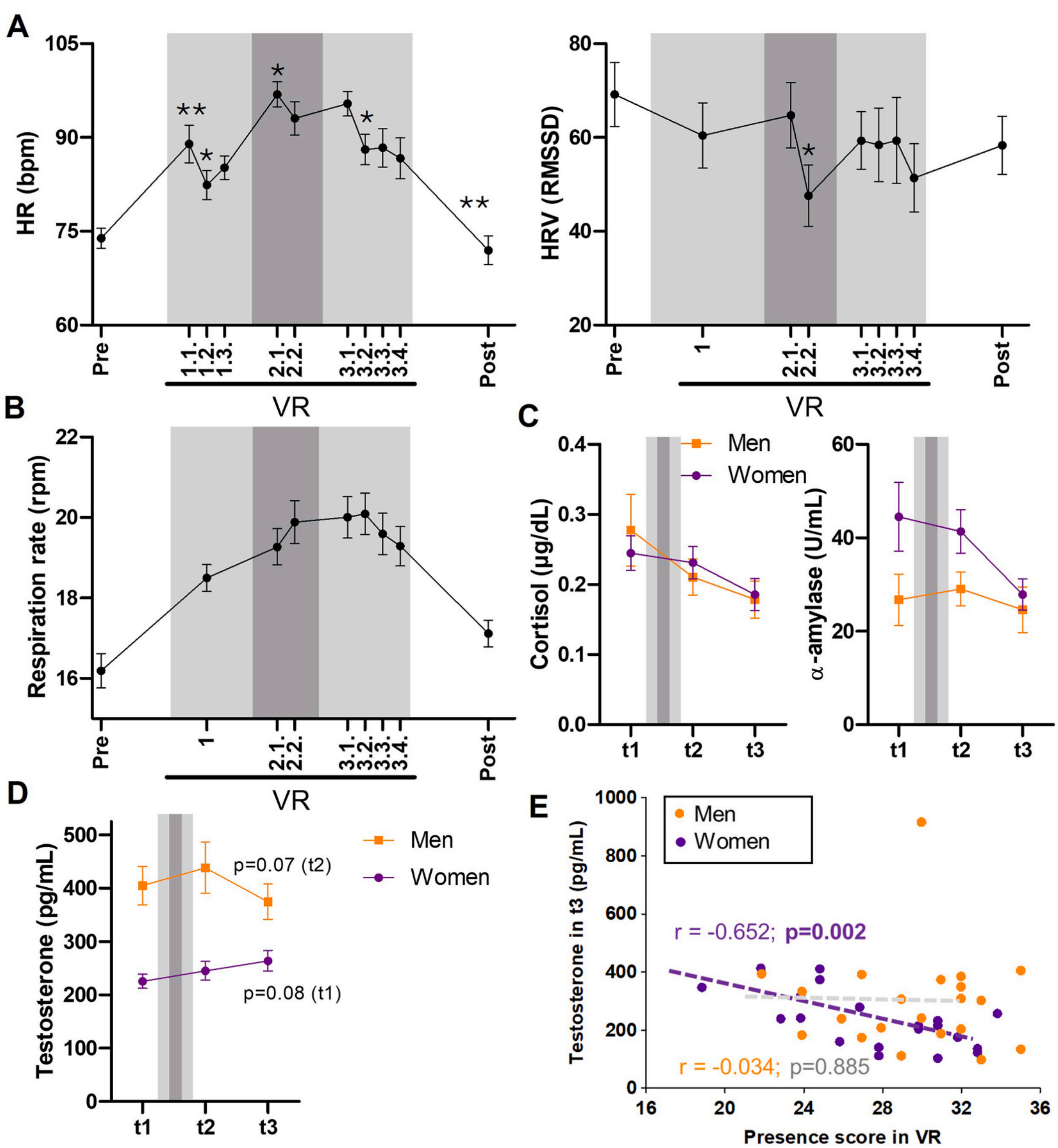

Fig. 2. Physiological response of the NCYA group to the VR tasks. A. Heart rate (HR) and heart rate variability (HRV) related to each VR scenario. Data presented as mean ± SEM. Pre (always 5 min), VR1. Face emotion task (total average time: 6 min); VR1.1 Emotion recognition task; VR1.2. Easy emotion discrimination task; VR1.3. Difficult emotion recognition task; VR2.1. Game task before frustration; VR2.2. Frustration (ambiguous situation, total average time: 3 min); VR3.1. Game task before frustration; VR3.2. Frustration (anger situation), 90 s split into three parts of 30 s (3.2., 3.3., 3.4.); Post (always 5 min). **B.** Respiration rate. **C.** Cortisol and alpha-amylasa response before (t1) and after the VR session (t2, immediately after; t3, 7 min later). **D.** Tendency towards significance in the sex-specific testosterone response to VR. **E.** A statistically significant negative correlation was found between testosterone final measure (t3) and PQ score after VR only in the female group. *$p < 0.05$, **$p < 0.01$ vs. previous time point (Wilcoxon signed-rank test).

presented lower levels of presence in VR (PQ, U = 141, p = 0.02; Table 1).

For self-reported Activation measured by SAM, significant differences were found pre/post (W = 3.188, p = 0.0014) and Control (W = 2.051, p = 0.04), but no statistically significant differences were found for self-reported emotional Valence nor between groups. When compared by sex, women showed no significant differences after exposure to the GINSO-VR protocol, whereas males presented significant difference in Activation (W = 2.691, p = 0.0071), but not in Valence nor Control.

No significant differences were shown between the cups' activities (VR2.1. vs VR2.1) in VR2 (ambiguous) and VR3 (anger) or HR, RMSSD and respiration variables, meaning that the changes in these variables during these time periods could be explained by the change within the activity and the "anger" stimuli. Significant differences were found between VR2.1 (cups task) vs V2.2 times for HR, RMSSD and Respiration (Fig. 2A–C). Significant differences were found between VR3.1 (cups task) vs VR3.2., VR3.3., VR3.4 (anger) 2or HR, but not for RMSSD nor Resp. No differences were found in the duration of the "anger" stimuli in T4 (1, 2, 3) for HR nor RMSSD, although significant differences were found for Resp between VR3.2 vs VR3.4 (anger), but not in the other conditions.

Friedman ANOVA showed significant differences across time-points for Heart Rate (HR) ($\chi^2(11) = 228.912$; $p < 0.001$), HR Variability (RMSSD) ($\chi^2(8) = 23.893$; $p = 0.0024$), and Respiration ($\chi^2(8) = 69.462$; $p < 0.001$). Significant changes were also observed in all frequency bands for EEG (Delta, Theta, Beta and Alpha), with no apparent difference in frontal and temporal electrodes. Within the hormonal measures, cortisol and alpha-amylase showed a significant change across conditions, but testosterone was not significant. When running Wilcoxon tests for cortisol and alpha-amylase, the differences were not significant for *t1 vs t2 for* either condition, but they were significant for t1 vs t3 (Cort W = 3.125; p = 0.002; a-Amyl W = 2.6175; p = 0.009) and t2 vs t3 (Cort W = 3.321; p = 0.0009; A-Amyl W = 4.235; p = 0.00002; Fig. 2C–D). Regarding sex-specific changes, we observed different patterns of testosterone curve (tendency to increase in women and decrease in males, Fig. 2D), which correlated significantly with the presence score (PQ) in VR in females (r = −0.652; p = 0.002) but not in males (r = −0.034; p = 0.885). This is relevant for the VR experience given also the differences in SSQ, in which females tend to show higher scores (Table 1).

When comparing pre-post measurement for EEG and HR variables (HR, RSSMD, Respiration, frontal Alpha, temporal-parietal Alpha, frontal Beta, temporal-parietal Beta) using Wilcoxon tests, no significant differences were found, but for Respiration pre/post (p = 0.0006). However, significant differences were observed when comparing frontal Alpha VR1, VR2, VR3 vs Pre and Post moments, but no statistically significant differences were found among VR1, VR2 and VR3. When running Wilcoxon test for frontal Beta power, significant differences were found between VR2, VR3 vs Pre and Post, as well as VR2 and VR3 when compared to VR1 (Fig. 3).

Lastly, multiple linear regression with backward elimination was conducted including all biological predictors of state anger (STAXI-S Post). The final model explained a significant proportion of the variance (adjusted $R^2 = 0.875$, $p < 0.001$). Regarding cardiac measures, HR during VR emotion was negatively associated with state anger ($\beta = -1.397$, $p < 0.001$), while HR in basal state (Pre; $\beta = 0.758$, $p < 0.001$) and HR during VR anger ($\beta = 1.247$, $p < 0.001$) were positively related. Basal RMSSD (Pre) showed a negative association ($\beta = -0.808$, $p < 0.001$), whereas RMSSD in VR anger was positively associated ($\beta = 0.727$, $p < 0.001$). With concern to EEG, only a moderate positive influence was found between frontal alpha in VR ambiguous situation and anger state post ($\beta = 0.217$, $p = 0.031$). Among the hormonal predictors, basal cortisol and testosterone (Pre) emerged as significant negative predictors ($\beta = -0.737$ and $\beta = -0.656$ respectively, $p < 0.001$), whereas in the Post measures contributed positively ($\beta = 0.952$, $p <$

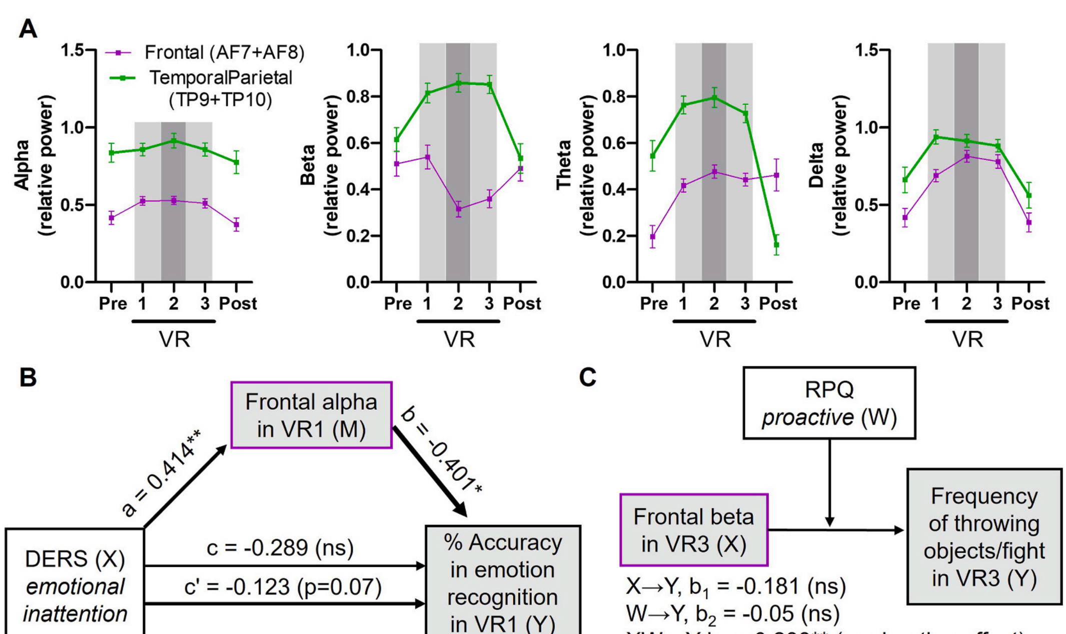

Fig. 3. Results of EEG signal before, during and after VR tasks. A. EEG relative power for frontal and temporal-parietal electrodes of Muse-2 device. VR, virtual reality tasks: VR1. Emotion recognition task; VR2. Ambiguous situation; VR3. Anger situation. **B.** Mediation model for accuracy in emotion recognition during VR. Results indicated evidence of full mediation: the total effect of emotional inattention on accuracy (path *c*) showed a tendency towards significance ($p = 0.0704$) but became non-significant when controlling for EEG alpha power (path c', $p = 0.4494$). The indirect effect via alpha power was significant (bootstrapped 95% CI: [-0.6186, −0.0461]), indicating that alpha power completely mediated the association between emotional inattention and accuracy. **C.** Moderation model for the frequency of throwing objects or trying to fight against the avatars during anger situation (VR3). The model shows a significant interaction between frontal beta power and RPQ proactive ($b_3 = 0.288$, $p = 0.0046$), indicating that the effect of beta on the frequency of throwing objects or fighting the avatar varies depending on sex. *p < 0.05, ** = p < 0.01, ns: non-significant.

0.001 and β = 0.43, p < 0.01, respectively). Interestingly, an inverse pattern was observed in alpha-amylase levels, with a positive association in t2 (β = 0.815, p < 0.001) and negative association in Post measurement (β = −0.737, p < 0.001). Even though all biological predictors (cardiac, EEG and hormonal measures) were initially included in the model, during the backward elimination process non-significant variables were removed and pooled by the software. These variables did not remain in the final model, being HR during the ambiguous situation and post VR, RMSSD during the emotion recognition and post VR, cortisol in t2 and alpha-amylase in t1 (Pre).

4. Discussion

This pilot study examined the psychological, behavioral and physiological responses to a set of immersive VR scenarios designed to intervene in aggression-related processes in adolescents and young adults. Overall, our findings suggest that immersive VR may be a useful tool for experimentally eliciting and studying anger and potentially aggressive responses within controlled environments, providing a basis for future research exploring its possible applications in therapeutic contexts (Alonso-Valerdi et al., 2025; Lambe et al., 2026). This sort of intervention could be very useful to treat aggression through increased awareness and skills training (González-Moraga et al., 2024; Jo et al., 2022). Additionally, this study suggests that neurobiological variables should be taken into account considering the robust statistical association with the increase in anger state after the VR exposure (See multiple linear regression results).

Consistent with previous studies (Sappelli et al., 2025; reviewed in Roncero et al., 2025), both clinical and control participants showed heightened levels of state of anger (STAXI-S) after exposure to provocative VR situations, supporting the effectiveness of VR to simulate real-life circumstances and contexts that elicit anger states. In our study, the NCYA group demonstrated significant changes in perceived activation and control in SAM test, suggesting that VR effectively engaged their emotional and physiological systems, in line with VR's immersive impact (Jo et al., 2022). On the other hand, the CA group displayed higher aggression scores in AQ and RPQ, and hostility (AQ) than the NCYA group, and a heightened change in STAXI-S that correlated with cannabis use. Plus, although there was not significant difference between groups in the frequency of throwing or fighting the avatars during the anger situation (VR3), the amount of time looking at the avatars was higher in the clinical group. This, together with the lower accuracy in emotion recognition of the avatars, could be interpreted as an indirect indicator of the hostile attribution bias (Martinelli et al., 2018; Singh, 2020).

In terms of intervention relevance, these findings are aligned with VR-based aggression interventions showing both promise and limitations (Roncero et al., 2025). Tuente et al. (2020) found improvements in anger control and aggression post VR intervention that were not maintained at follow-up, while Woicik et al. (2023) and Ivarsson et al. (2023) reported more sustained effects. Similarly, CBT-based VR programs for anger control have shown efficacy in adolescents (Alsem et al., 2023; Jo et al., 2022), although long-term generalization remains inconsistent. Additionally, it is interesting to note that the scores in presence and simulator sickness are comparable to previous data using VR (Hirzle et al., 2021; Kourtesis et al., 2023).

Furthermore, physiological responses further support the validity of GINSO-VR. In the NCYA group, HR, RMSSD, EEG activity, cortisol, testosterone and alpha-amylase all varied significantly across VR phases, indicating dynamic engagement of stress systems (Sousa, 2016). These findings shed light on how control groups react to these immersive VR situations and can help to identify when the response is abnormal. Among other variables, HR and RMSSD values significantly predicted post-VR state anger. Regarding RMSSD as a form of HR variability, lower basal levels are related to higher change in anger post (β = −0.808, p < 0.001), which agrees with previous findings (Palix et al., 2017).

At the neurophysiological level, contrary to earlier findings that linked frontal alpha asymmetry with aggressive behavior in adolescents (Peterson et al., 2008; Rybak et al., 2006), we did not replicate this association. However, regardless of the hemisphere, mediation analysis revealed that frontal alpha power fully mediated the relationship between emotional inattention and task accuracy in the NCYA group. Indeed, previous evidence also agrees that frontal alpha power plays an important role in the discrimination of facial expression of emotions (Balconi & Ferrari, 2012). This suggests that alpha wave increase may indicate inhibitory control processes relevant to aggression regulation, as supported by previous evidence of slow-wave alterations in aggressive youth (Im et al., 2019). Additionally, proactive aggression (RPQ) moderated the relationship between beta power and aggressive behavior in the NCYA group (Fig. 3C), which partially agrees with previous findings (Hofman & Schutter, 2012). However, this also contrasts with the study of Aggensteiner et al. (2022), who observed a negative correlation between beta power and RPQ proactive in clinical populations, but non-significant in the control group, whereas our results show a positive influence of beta power in our control group. This discrepancy suggests that the role of relative beta power may differ depending on psychological status (Feng et al., 2024; Sprague et al., 2011), and the role in our clinical group is one of the future directions, which could align with Aggensteiner et al. (2022).

Our study stretches this literature by identifying both EEG relative power and HR variability as potential biomarkers to adapt VR interventions to individual aggression profiles, supporting potential biofeedback approaches in this population (Dashbozorgi et al., 2021; Haneveld et al., 2025; Hillman, 2025). Also, the EEG device employed in this research is a commercially available, low-cost system that is easily accessible and simple to set up, requiring no specialized analytical expertise on the part of the therapist, and can therefore be feasibly implemented in clinical settings.

On the other hand, the interplay between salivary hormones and aggression is quite complex and has been recently reviewed by Cima et al. (2025). Our results are proof of this complexity, in which lower levels cortisol and testosterone related to higher anger states Post (β = −0.737 and β = −0.656 respectively, p < 0.001), but higher levels of these hormones after the VR exposure led to higher scores in anger (β = 0.952, p < 0.001 and β = 0.43, p < 0.01, respectively). The mixed results in the scientific literature can be partially explained by the moment of measurement, which is key to understanding the temporal dynamics that leads to anger and aggression. In our data, alpha-amylase seems to be particularly sensitive to the timing of measurement, in which the levels the moment immediately after VR exposure (t2) was positively associated with anger scores (β = 0.815, p < 0.001), but 10 min the association was reversed (β = −0.737, p < 0.001). This agrees with previous findings, in which the immediate peak of sympathetic activity and fast recovery can be representative of the increased emotional state (Moreno-Fernández et al., 2023; Whinery et al., 2022).

Taken together, these findings underscore the multidimensional nature of aggression, where emotional, psychological, social, physiological, and brain systems converge. Importantly, the responses during GINSO-VR to the STAXI-S test right after the provocative experience were representative of the neurobiological factors assessed in this study. This evidence also emphasizes VR's feasibility as a therapeutic tool, since not only VR elicits ecologically valid aggression-related responses in a controlled environment, but it also enables simultaneous assessment of behavioral and physiological markers. Even though only a single VR exposure was carried out, these results highlight the need for a therapeutic approach with several sessions for working on these controlled situations and eventually reducing this type of interacting antisocial behaviors (aggression, hostility and drug consumption) in clinical population. However, as presented here, only one VR session with low sample sizes leading to nonparametric analysis implies significant limitations such as weak ecological validity and limited long-term evaluation. Also, despite the high number of variables and data collected from each participant, the relatively small sample size and the variability across participant subgroups may limit the generalizability of the findings and the statistical power to detect smaller effects. In addition, although we included comparisons with the nonclinical young adult group (NCYA) and the clinical adolescent group (CAG), neither of these groups constitutes a control group; rather, they provide a reference to observe patterns across different types of samples. Additionally, biological data for our clinical group is lacking. Future research should replicate these findings using larger samples and multi-session randomized controlled trial to confirm the robustness and stability of the observed effects. Indeed, young people in social conflict require a rather broad multifaceted therapeutic strategy to promote effectively their biopsychosocial well-being. These limitations highlight the need for future larger, longer and structured studies to fully understand and validate the efficacy of GINSO-VR intervention.

CRediT authorship contribution statement

Román D. Moreno-Fernández: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Candela Reyes-Rubio:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Álvaro Fernández-Moreno:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Patricia Sampedro-Piquero:** Writing – review & editing, Project administration, Investigation, Conceptualization. **Carlos Benedicto-Duque:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition. **David Roncero:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Artificial intelligence (AI) statement

During the preparation of this work the authors used Scopus AI, DeepL Write and OpenAI in order to find specific references for determined topics, help with language translation and improve readability and language, respectively. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chbr.2026.101116.

Data availability

Data will be made available on request.

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