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Virtual reality enhanced mindfulness and yoga intervention for postpartum depression and anxiety in the post COVID era

Nan Liu[1], Junchen Deng[2]✉, Fang Lu[1]✉ & Juan Xiao[3]

The postpartum period has witnessed increasing rates of depression and anxiety, particularly in the context of the COVID-19 pandemic, with these conditions often co-occurring and being exacerbated by the lingering effects of long COVID. Traditional interventions, such as mindfulness-based stress reduction (MBSR) and yoga, have demonstrated effectiveness in alleviating these symptoms. However, the limitations of in-person sessions, especially in the context of pandemic-related restrictions, highlight the need for accessible, innovative approaches. Integrating Virtual Reality (VR) technology with these traditional practices presents a novel solution, offering immersive, customizable environments that may enhance engagement and therapeutic outcomes. This study evaluates the effectiveness of a VR-enhanced mindfulness and yoga intervention in treating postpartum depression and anxiety in women affected by long COVID, with additional examination of underlying physiological stress markers and cognitive control mechanisms. In this randomized controlled trial, 111 postpartum women were randomly assigned to experimental (VR-enhanced intervention), control (traditional in-person sessions), or blank groups using computer-generated randomization. The 8-week intervention involved thrice-weekly 60-minute sessions. Outcomes were assessed at baseline, post-intervention, and 4-week follow-up using the Edinburgh Postnatal Depression Scale (EPDS), Generalized Anxiety Disorder-7 (GAD-7) scale, salivary cortisol measurements, and an emotional Stroop task. The VR-enhanced intervention group demonstrated significant improvements in both depression (EPDS: $P<0.001$, $\eta_p^2=0.18$) and anxiety symptoms (GAD-7: $P<0.001$, $\eta_p^2=0.17$), with these therapeutic effects significantly greater than those observed in the control and blank groups ($P<0.001$ for both comparisons). These improvements were strongly correlated ($r=0.68$, $P<0.001$). Supporting these primary outcomes, salivary cortisol levels showed a significant decrease ($P<0.001$, $\eta_p^2=0.13$), and cognitive control improved as evidenced by reduced emotional Stroop task conflict effect ($P<0.001$, $\eta_p^2=0.37$). Correlation analysis revealed robust associations between improvements in depression and anxiety symptoms and changes in physiological markers in both short-term and long-term outcomes. This study demonstrates that integrating VR technology with traditional mindfulness and yoga practices effectively reduces both postpartum depression and anxiety symptoms in the post-COVID era. The parallel improvements in physiological stress markers and cognitive control provide insight into potential mechanisms underlying these therapeutic effects. These findings underscore the value of immersive technology in enhancing traditional therapeutic approaches for addressing postpartum depression and anxiety in the post-pandemic context.

Keywords Postpartum, Virtual reality (VR), Mindfulness-Based, Yoga, COVID, Depression, Anxiety, Cognitive control

The COVID-19 pandemic has profoundly reshaped the landscape of maternal mental health, exacerbating pre-existing challenges and creating new ones for postpartum women. Recent epidemiological data indicate that the prevalence of postpartum depression and anxiety has surged by 25% since the onset of the pandemic, with up to 30% of new mothers now experiencing clinically significant symptoms[1]. This alarming increase

[1]India-China Yoga College, Yunnan Minzu University, Kunming, China. [2]College of Sport Arts, Guangzhou Sport University, Guangzhou, China. [3]Dongguan City Electronic Commerce School, Dongguan, China. ✉email: 11492@gzsport.edu.cn; 040692@ymu.edu.cn

is attributed not only to the direct impacts of COVID-19 infection but also to the pervasive effects of "long COVID", characterized by persistent fatigue, cognitive impairments, and mood disturbances[2–5]. The pandemic has also disrupted traditional support systems and healthcare delivery models, with a 50% reduction in face-to-face postpartum care visits reported globally[6]. This confluence of factors—biological, psychological, and social—has created a "perfect storm" for maternal mental health crises, underscoring the urgent need for innovative, accessible interventions tailored to the unique challenges of the post-pandemic era.

Traditional interventions for postpartum mental health, such as mindfulness-based stress reduction (MBSR) and yoga, have shown promise in alleviating symptoms of depression and anxiety[7,8]. A meta-analysis of 18 randomized controlled trials found that MBSR can reduce depressive symptoms with a moderate effect size[9]. Similarly, yoga interventions have demonstrated efficacy in improving mood and reducing stress in postpartum women[10]. However, these approaches face significant limitations in the post-pandemic context. Adherence to in-person interventions has declined by 40% since 2020, partly due to concerns about viral transmission and competing demands on new mothers' time[11]. Moreover, traditional interventions often fail to address the multifaceted nature of postpartum distress, which encompasses cognitive, emotional, and physiological dimensions[12]. The one-size-fits-all approach of many existing programs also fails to account for the diverse and individualized needs of postpartum women, particularly those experiencing the compounded stressors of the pandemic era. This gap in current treatment modalities underscores the need for innovative approaches that can provide comprehensive, accessible, and personalized interventions tailored to the unique challenges faced by postpartum women in the post-pandemic world.

Virtual Reality (VR) technology emerges as a promising solution to address these limitations, offering advantages beyond conventional remote delivery methods such as video conferencing or recorded content. Unlike traditional digital platforms, VR creates immersive, controlled environments that enhance engagement through three-dimensional spatial awareness and real-time postural feedback. The technology enables customizable practice environments that can be adjusted to individual comfort levels while maintaining the therapeutic benefits of traditional practices. Furthermore, VR's capacity for biofeedback integration allows for monitoring and adjusting practice intensity based on physiological responses, a feature unavailable in conventional remote delivery formats. The application of VR in mental health treatment has evolved significantly over the past two decades, with notable successes in treating anxiety disorders, PTSD, and phobias[13]. In mental health applications, VR has demonstrated efficacy comparable to or exceeding traditional in-person therapies, with a meta-analysis reporting an effect size of Cohen's $d = 0.9$ for anxiety disorders[14]. Recent controlled trials have further validated these findings, showing significant reductions in state anxiety and enhanced engagement when VR is integrated with relaxation techniques[15]. Technological advances have significantly improved user experience and accessibility, making VR increasingly viable for widespread implementation in maternal mental health care[16]. The integration of VR with mindfulness and yoga practices represents a novel approach that capitalizes on the strengths of both traditional and technological interventions[17,18]. This combination shows particular promise for postpartum populations, where engagement and adherence have traditionally been challenging to maintain[19].

Beyond conventional approaches using generic relaxing environments, VR technology enables the creation of personalized therapeutic content based on individual life experiences and preferences[20]. This user-centered approach to VR design may facilitate more sophisticated and sustained relaxation effects, particularly valuable for postpartum women navigating pandemic-era challenges[21]. The technology allows for precise calibration of virtual environments to individual recovery trajectories and cultural preferences[22], while the immersive nature of VR facilitates deeper engagement with mindfulness practices through reduced external distractions[23]. However, the efficacy of VR-based mindfulness and yoga interventions for postpartum women, particularly in the post-pandemic context, remains largely unexplored, presenting a critical gap in our understanding of innovative mental health interventions for this vulnerable population.

The potential efficacy of VR-enhanced mindfulness and yoga interventions is underpinned by the intricate relationship between cognitive control, emotional regulation, and physiological stress responses. This study employs a comprehensive assessment approach, integrating self-report measures (Edinburgh Postnatal Depression Scale and Generalized Anxiety Disorder-7), physiological markers (salivary cortisol), and cognitive tasks (emotional Stroop task) to provide a holistic understanding of the intervention's impact. Cognitive control, a key executive function, plays a crucial role in modulating emotional responses and has been found to be impaired in postpartum women experiencing depression and anxiety[24]. Neuroimaging studies have revealed that mindfulness practices can enhance activity in the prefrontal cortex and reduce amygdala reactivity, leading to improved emotional regulation[25]. These neural changes are particularly relevant for postpartum women, who often experience heightened emotional reactivity and decreased cognitive control due to hormonal fluctuations and sleep deprivation[26,27]. Concurrently, yoga has been shown to reduce cortisol levels, a primary physiological marker of stress, by up to 31% in postpartum women[28]. The integration of these practices within a VR environment may amplify these effects through enhanced engagement and multisensory stimulation, potentially leading to more significant improvements across all measured outcomes.

Of particular interest in our assessment battery is the emotional Stroop task, which serves as a robust measure of cognitive control and emotional regulation. This task, which requires participants to name the color of emotionally charged words while ignoring their meaning, assesses the ability to maintain cognitive control in the face of emotional interference[29]. The conflict effect, measured as the difference in response times between congruent and incongruent trials, quantifies the degree of emotional interference on cognitive processes[30]. In postpartum women, a larger conflict effect has been associated with increased vulnerability to depression and anxiety, reflecting difficulties in emotional regulation[31]. VR-based interventions have the potential to directly target and improve performance on this task by enhancing attentional control and reducing emotional reactivity. Preliminary studies have shown that VR-based cognitive training can reduce the emotional Stroop effect in individuals with anxiety disorders[32], suggesting its potential efficacy for postpartum women. By incorporating the emotional Stroop task alongside other validated measures, our study aims to provide a comprehensive assessment of the cognitive, emotional, and physiological impact of VR-enhanced mindfulness and yoga interventions.

Given the compelling evidence for the potential of VR-enhanced mindfulness and yoga interventions, coupled with the urgent need for innovative approaches to address postpartum mental health in the post-pandemic era, this study aims to evaluate the multidimensional effects of a VR-based mindfulness and yoga intervention on the psychological health of postpartum women. Specifically, we seek to answer four key questions: (1) To what extent does a VR-based mindfulness and yoga intervention reduce symptoms of depression and anxiety in postpartum women compared to traditional interventions and no intervention? (2) How does this novel approach impact cognitive control and emotional regulation, as measured by reaction times and accuracy rates in both congruent and incongruent conditions of an emotional Stroop task? (3) What is the effect of the intervention on emotional conflict resolution, as indicated by the conflict effect (difference between incongruent and congruent trials) in the emotional Stroop task? (4) What are the physiological effects of the intervention, as indicated by changes in salivary cortisol levels? We hypothesize that the VR-based intervention will lead to significantly greater improvements in all measured outcomes compared to both traditional interventions and no intervention, including reduced emotional conflict effect and improved performance in the emotional Stroop task. This randomized controlled trial employs a comprehensive assessment approach, integrating self-report measures, cognitive tasks, and physiological markers to provide a holistic understanding of the intervention's efficacy. By addressing these questions, this study aims to bridge the gap between technological innovation and clinical practice in maternal mental health, potentially paving the way for more effective, engaging, and accessible interventions for postpartum women in the post-pandemic world. Moreover, by including a follow-up assessment, we aim to evaluate the long-term efficacy of the intervention, addressing a critical gap in current research on VR-based mental health interventions.

Materials and methods

Participants, randomization, and blinding procedures

A priori power analysis using G*Power 3.1 determined a required total sample size of 81 participants (27 per group) to detect a medium effect size ($f = 0.25$, $\alpha = 0.05$, power = 0.80) in our mixed-design analysis. The study included 149 postpartum women recruited from three fitness centers in Guangzhou and Kunming, China. Initial screening based on specific inclusion and exclusion criteria resulted in the exclusion of 38 individuals. The remaining 111 participants were strictly randomized into experimental, control, and blank groups (37 participants per group) using a computer-generated 1:1:1 sequence of assigned random numbers. The randomization sequence was generated prior to participant enrollment and was concealed from the recruitment team until group assignments were made.

Due to the nature of the intervention involving VR equipment, complete participant blinding was not feasible, as participants required proper orientation and familiarization with the VR devices to ensure safe and effective participation. However, to minimize potential bias, data analysts were blinded to group allocation during the statistical analysis phase. During the study, attrition occurred due to personal reasons or uncontrollable factors, with 8 participants from the experimental group, 9 from the control group, and 4 from the blank group excluded for non-compliant data. After data processing and cleaning, the final sample comprised 90 participants: experimental group ($n = 29$), control group ($n = 28$), and blank group ($n = 33$), exceeding the minimum required sample size while maintaining experimental rigor.

The inclusion criteria required participants to be postpartum women aged 22–40 years, with a history of COVID-19 infection during the pandemic and/or post-pandemic period, and without previous mindfulness meditation or yoga experience, or with minimal experience in either practice (total training duration less than 2 h for each). Additional criteria included no prior experience with VR, being physically healthy without symptoms of cold or fever, not currently or previously on antidepressant medication, having normal or corrected vision without color vision deficiencies, and no history of 3D motion sickness or claustrophobia. The exclusion criteria included severe mental health conditions unrelated to postpartum depression or anxiety, inability to participate in VR mindfulness or yoga sessions, any contraindications to moderate physical activity, never having been infected with COVID-19, or not having fully recovered from a COVID-19 infection.

Demographic characteristics of the participants are presented in Table 1. The majority of participants across all groups had college or graduate education (81.82–82.76%), while 17.24–18.18% had no college education. Most participants were partnered (79.31–82.14%), with the remainder being single, divorced, or widowed. Approximately 55–57% were experiencing their first pregnancy, while 43–45% had prior pregnancies. The experimental group had a mean age of 30.45 years (SD = 5.34), the control group 30.48 years (SD = 5.36), and the blank group 30.45 years (SD = 5.35) (Table 1).

Participants completed baseline assessments (T1), followed by an 8-week intervention period with post-intervention assessments (T2), and a follow-up assessment 4 weeks after the intervention ended (T3). The assessments included self-reported measures of depression (Edinburgh Postnatal Depression Scale, EPDS) and anxiety (Generalized Anxiety Disorder-7, GAD-7). At baseline, mean EPDS scores were 8.61 (SD = 4.65), 8.25 (SD = 4.28), and 8.98 (SD = 3.97) for the experimental, control, and blank groups, respectively. Mean GAD-7 scores were 6.85 (SD = 6.45), 7.27 (SD = 6.33), and 6.91 (SD = 6.36) for the respective groups (Table 1).

Detailed information on COVID-19 infection history and severity was collected (Table 1). During the pandemic, participants experienced a mean of 1.34–1.39 COVID-19 infections across the three groups. The severity during this period was predominantly mild (62.07–64.29%), with moderate cases ranging from 17.24 to 18.18%, and severe cases from 17.86 to 20.69%. In the post-pandemic period, the mean number of infections ranged from 1.54 to 1.56 across groups. The severity during this period was mostly mild (79.31–82.14%), with moderate cases ranging from 12.12 to 14.29%, and severe cases from 3.57 to 6.90%.

Characteristic	Experimental group (n = 29)	Control group (n = 28)	Blank group (n = 33)
Age (years)	30.45 (5.34)	30.48 (5.36)	30.45 (5.35)
Education	–	–	–
No college	17.24%	17.86%	18.18%
College or graduate education	82.76%	82.14%	81.82%
Relationship status	-	-	-
Partnered	79.31%	82.14%	81.82%
Single, divorced, or widowed	20.69%	17.86%	18.18%
Parity	–	–	–
First pregnancy	55.17%	57.14%	54.55%
Prior pregnancies	44.83%	42.86%	45.45%
COVID-19 infection times (pandemic)	1.34 (1.12)	1.38 (1.13)	1.39 (1.14)
COVID-19 severity (pandemic)	–	–	–
Mild	62.07%	64.29%	63.64%
Moderate	17.24%	17.86%	18.18%
Severe	20.69%	17.86%	18.18%
COVID-19 infection times (post-pandemic)	1.55 (1.09)	1.54 (1.08)	1.56 (1.10)
COVID-19 severity (post-pandemic)	–	–	–
Mild	79.31%	82.14%	81.82%
Moderate	13.79%	14.29%	12.12%
Severe	6.90%	3.57%	6.06%
EPDS	8.61 (4.65)	8.25 (4.28)	8.98 (3.97)
GAD-7	6.85 (6.45)	7.27 (6.33)	6.91 (6.36)

Table 1. Sample characteristics and descriptive statistics for postpartum psychological health and COVID-19 related variables.

This study is registered with the Chinese Clinical Trial Registry (ChiCTR) (Registration number: ChiCTR2400091333, registration date: 25/10/2024). The study was conducted in accordance with the Declaration of Helsinki, and ethical approval was obtained from the Institutional Review Board (IRB) of Yunnan Minzu University (IRB#: YXLL2024001). All participants provided written informed consent before participating in the study.

Procedure

This study evaluates the efficacy of a VR-enhanced mindfulness and yoga intervention on the physical and mental health of postpartum women in the post-pandemic era. Participants are allocated to three groups: the Experimental Group, undergoing the VR-based mindfulness and yoga intervention; the Control Group, participating in traditional in-person mindfulness and yoga sessions guided by professional instructors; and the Blank Group, receiving no specific intervention. The intervention period for all groups spans 8 weeks, with sessions conducted thrice weekly, each lasting 60 min (FIGURE 1).

VR-enhanced mindfulness and yoga for experimental group

The Experimental Group received a comprehensive intervention combining VR-enhanced mindfulness and yoga practices. The intervention employed the Oculus Quest 2 VR headset, which provides an immersive experience through its high-definition LCD screen, Qualcomm Snapdragon XR2 processor, and 6GB of RAM, delivering a single-eye resolution of 1832 × 1920 with refresh rates of 72 Hz and 90 Hz.

All sessions were conducted in designated rooms at participating fitness centers under the supervision of a Nationally Certified Yoga and Mindfulness Senior Trainer from India-China Yoga College, Yunnan Minzu University. Sessions were organized in small groups of 6–8 participants, maintaining an optimal instructor-to-participant ratio (1:6–8). This format balanced individualized attention with peer support benefits while ensuring proper monitoring of form and safety. The small group setting facilitated community building among postpartum women while maintaining professional oversight.

Each session began with a 15-minute mindfulness practice facilitated through the Supernatural app, a subscription-based immersive platform offering customizable meditation environments. Participants could select from three distinct virtual environments:

(1) Bolivian Salt Flats: A serene setting designed to reduce stress and improve mood through calming visual and auditory stimuli.
(2) Icelandic volcano: A Stark, dramatic landscape enhancing cognitive focus and mental clarity
(3) Lunar surface: A tranquil, isolated environment deepening meditation and promoting mental detachment from daily stressors

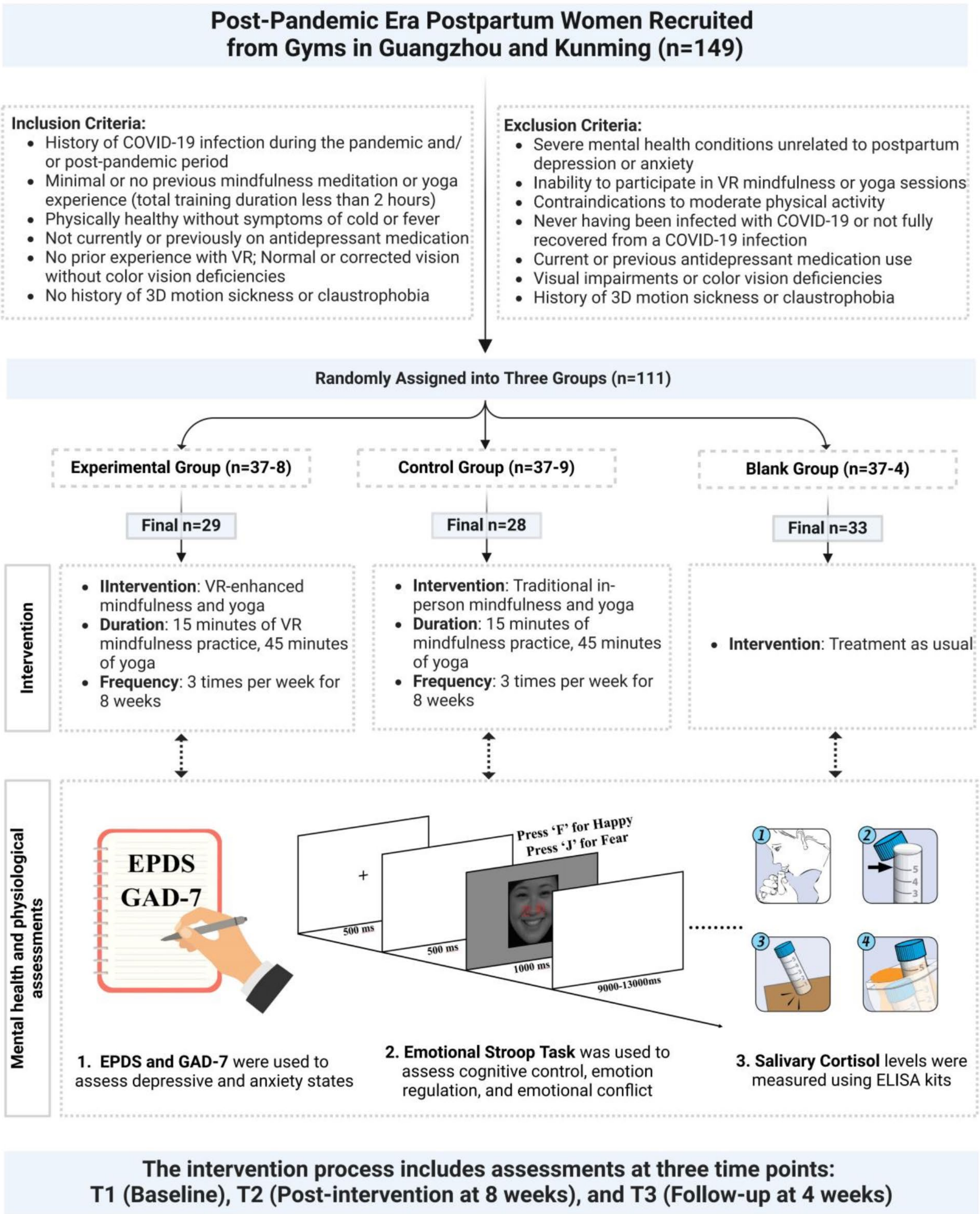

Fig. 1. Enrollment, intervention, and assessment procedures. The study was conducted from August 2024 to November 2024. Initial recruitment and screening occurred in August 2024, identifying 149 eligible participants. After applying inclusion/exclusion criteria, 111 participants were randomized into three groups in early August 2024. The 8-week intervention phase was conducted from August to October 2024, with assessments at baseline (T1), post-intervention (T2, October 2024), and 4-week follow-up (T3, November 2024). Final data collection and analysis were completed by November 2024.

After completing the 15-minute mindfulness exercises, participants transitioned into a 45-minute VR yoga session using the Oculus Quest 2 headset. These sessions were guided by a three-level progression structure, which was carefully designed based on established postpartum yoga therapy guidelines, blending traditional yoga practices with modern exercise science principles. The "Anti-COVID" module from Yoga Master was utilized to implement this structured progression, ensuring a systematic and evidence-based approach to postpartum recovery.

(1) Beginner Sessions (Weeks 1–3): Gentle, accessible asanas focusing on building foundational strength, breathing techniques (pranayama), and mental calm. This level emphasizes proper posture, core stability, and pelvic floor awareness - essential elements for postpartum recovery.
(2) Intermediate Sessions (Weeks 4–6): More challenging sequences incorporating balance poses, moderate strength-building exercises, and extended meditation periods. This level aims to promote resilience, enhance mind-body connection, and support stress reduction through more complex breathing patterns.
(3) Advanced Sessions (Weeks 7–8): Complex asanas integrating dynamic movements, sustained poses, and advanced breathing techniques. This level focuses on building confidence, emotional regulation, and sustained mindfulness practice.

Based on established postpartum yoga protocols, participants were expected to achieve at least intermediate-level competency by the end of the 8-week intervention, demonstrating proper form in fundamental poses, stable breathing patterns, and improved mindfulness scores. Each VR session began with a 5-minute equipment setup and safety check, including headset calibration, virtual environment loading, and standardized verbal instructions for proper headset positioning and controller use.

The trainer conducted weekly assessments using standardized rubrics to evaluate three key domains: physical form accuracy (proper alignment and breathing), mindfulness practice quality (attention maintenance and relaxation depth), and technical adaptation (VR navigation proficiency). Advancement to the next difficulty level required achieving at least 80% proficiency in all three domains. While the progression was structured, the trainer could adjust the pace based on individual needs, ensuring each participant maintained proper form and received appropriate modifications when needed.

For quality control, two certified instructors independently reviewed participant form and progress during each session using a standardized checklist, resolving any assessment discrepancies through consultation. Emergency protocols were established for participants experiencing any discomfort, including immediate VR session termination if needed and modification options for challenging poses. Session compliance, progress metrics, and individual responses were systematically documented through attendance records, assessment forms, and post-session feedback.

While both the experimental and control groups conducted sessions in small groups of 6–8 participants, the nature of participant interaction was deliberately differentiated as an inherent aspect of the intervention modalities being compared. In the VR-enhanced intervention, participants were positioned in the same room with sufficient space (approximately 2 m apart) to allow for full range of motion without physical interaction. While wearing the VR headsets, participants could not visually perceive other participants or the physical environment, as the headsets provided complete visual immersion in the virtual environments. This deliberate isolation from external visual distractions is a core therapeutic mechanism of VR intervention, allowing for enhanced focus on interoceptive awareness and mindfulness states.

Instructions were provided through two complementary channels: (a) standardized audio guidance through the VR headset that was synchronized with visual cues in the virtual environment, and (b) verbal guidance from the in-person instructor who monitored form and provided individualized feedback when necessary. The instructor could observe participants' movements in physical space and provide tactile corrections to posture when needed, while participants remained visually immersed in the virtual environment.

The VR intervention was intentionally designed to leverage the therapeutic benefits of both group and individual formats. While participants experienced a sense of shared practice through awareness of others' presence in the room and the instructor's verbal guidance, the visual immersion created a protected psychological space that minimized social comparison and performance anxiety—factors that can impede therapeutic engagement for individuals with depression and anxiety. This approach aligns with research suggesting that postpartum women may benefit from reduced social evaluation during mind-body interventions[33].

The distinct interactive dynamics between the VR and traditional interventions represent a deliberate aspect of our study design rather than a methodological limitation. Our research question specifically aimed to evaluate whether the unique properties of VR-enhanced mindfulness and yoga (including its altered social dynamics) could provide superior therapeutic outcomes compared to traditional delivery formats. The significant improvements observed in the VR condition suggest that for this specific population, the benefits of immersive individual experience may outweigh those of increased social interaction.

To assess participants' overall intervention experience, we measured satisfaction using the Client Satisfaction Questionnaire (CSQ-8) developed by Attkisson and Zwick[34]. This standardized measure provided valuable insights into participants' perceptions of the intervention quality and appropriateness.

Traditional mindfulness and yoga for control group

The Control Group intervention was conducted by certified instructors from India-China Yoga College, maintaining the same instructor-to-participant ratio (1:6–8) as the VR intervention group. Participants attended thrice-weekly 60-minute sessions in small groups over the 8-week intervention period, matching the format of the VR intervention group. This standardization of delivery format across both conditions enabled controlled comparison of the intervention modalities.

Sessions maintained strict temporal equivalence with the VR intervention:

1) Mindfulness Sessions (15 min): Conducted in a quiet studio environment, these sessions focused on breath awareness, stress reduction, and emotional regulation through guided meditation practices.
2) Yoga Sessions (45 min): Delivered in small groups, these sessions comprised structured series of asanas following the same three-level progression as the VR group. Instructors provided guidance and adjustments to ensure proper alignment and technique.

The traditional in-person format facilitated both individual attention and group support, with instructors able to provide real-time corrections while maintaining a supportive practice environment. This careful matching of delivery format, timing, and progression between conditions ensures that observed differences in outcomes can be attributed to the intervention modality rather than other factors.

No intervention for blank group

The Blank Group serves as a baseline comparison, receiving no specific mindfulness or yoga intervention during the 8-week study period. Participants in this group continue their usual daily activities and routine care without any additional structured mindfulness or yoga practices. This group allows for the assessment of the natural progression of postpartum recovery without external interventions, providing a control for evaluating the effectiveness of the Experimental and Control group interventions.

Measures.

Edinburgh postnatal depression scale (EPDS)

The Edinburgh Postnatal Depression Scale (EPDS), developed by Cox et al.[35] and translated into Chinese by Lee et al.[36], was used to assess the depressive state of postpartum women[37]. The EPDS is one of the most commonly used screening tools for postpartum depression. The scale consists of 10 items that evaluate various aspects such as mood, pleasure, anxiety, self-blame, fear, insomnia, coping ability, sadness, crying, and self-harm. Each item is scored on a Likert scale from 0 to 3, with responses ranging from "never" to "always." The total score ranges from 0 to 30, with higher scores indicating more severe depression. In this study, an EPDS score of ≥ 9 was used as the cutoff for screening depression. The Cronbach's alpha coefficient of the scale is 0.832, indicating good internal consistency.

Generalized anxiety disorder scale (GAD-7)

The Generalized Anxiety Disorder Scale (GAD-7) was used to assess the anxiety state of postpartum women[38,39]. The GAD-7 was developed by Spitzer et al. in 2006 based on the diagnostic criteria for generalized anxiety disorder in the American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders. The scale consists of 7 items, each scored on a Likert scale from 0 to 3, with responses ranging from "not at all" to "nearly every day." The total score ranges from 0 to 21, with higher scores indicating higher levels of anxiety. Scores of 0–4 indicate no anxiety, 5–9 indicate mild anxiety, 10–14 indicate moderate anxiety, and 15 and above indicate severe anxiety. A cutoff score of 10 provides a sensitivity of 89% and a specificity of 82%. The Cronbach's alpha coefficient of the scale is 0.92, and the test-retest reliability is 0.83.

Salivary cortisol

Salivary cortisol concentrations were measured at three time points: one day before the intervention, one day after the 8-week intervention, and four weeks post-intervention during the follow-up. To avoid the influence of circadian rhythm on cortisol levels, saliva (1 mL) was collected by instructing participants to spit directly into a measuring tube between 2:00 PM and 4:00 PM on the assessment days[40]. Collected saliva samples were processed on the same day and stored at − 80 °C until further analysis.

To ensure the quality of the samples, participants were instructed not to engage in strenuous activities during the testing period. They were also asked to refrain from rinsing their mouths or eating before arriving at the testing site. To maintain good oral hygiene, participants were prohibited from drinking alcohol and smoking before and after the test. Participants rinsed their mouths with plain water, discarded the first mouthful of saliva, and then provided a sample by spitting directly into the measuring tube.

Cortisol levels in the saliva samples were measured using commercially available enzyme-linked immunosorbent assay (ELISA) kits from Enzo Life Sciences (Farmingdale, NY, USA) in duplicate per sample, following the manufacturer's instructions[41,42]. The detection range of the cortisol ELISA kit was 156–10,000 pg/ml. To avoid inter-assay variation, the pre- and post-samples of the same participant were analyzed using the same ELISA kits. None of the collected samples showed signs of hemolysis or other abnormalities, and all sample results were retained for analysis.

Emotional stroop task

The emotional conflict task employed an emotional face-word Stroop paradigm[29]. The stimuli were selected from the Chinese Affective Picture System (CAPS), consisting of 20 happy and 20 fearful facial images, equally divided between male and female faces. The recognition rate for happy faces was $96.36 \pm 5.11\%$, with an intensity of 5.38 ± 1.11, while the recognition rate for fearful faces was $70.84 \pm 6.62\%$, with an intensity of 6.50 ± 1.23. Each facial image was labeled with either the word "happy" or "fearful" in red ink. These images were processed using Photoshop CC 2019 to standardize the contrast and brightness, and resized to 240×180 pixels. The experimental program was developed using E-Prime 4.0, with stimuli presented in a random order.

The experiment was conducted in a controlled lighting laboratory, with individual testing sessions. Participants first provided demographic information and then sat approximately 60 cm from a computer screen.

The experiment began with the following instructions: "Welcome to our experiment! You will see a '+' fixation point on the screen. Please focus on the center of the screen. Then, a target stimulus will appear in the center. Make a response by pressing a key, after which the stimulus will disappear, and the screen will go blank before the next trial begins." The fixation point was displayed for 500 ms, followed by a blank screen for 500 ms, and then the stimulus appeared. Participants were instructed to judge the facial expression while ignoring the word. If the expression was happy, they pressed the "F" key, and if it was fearful, they pressed the "J" key. The stimulus remained on the screen for 1000 ms, with an inter-trial interval of 9000–13,000 ms. The system automatically recorded the reaction time and accuracy of responses within a 1500 ms window.

In this task, participants viewed a series of emotional facial images labeled with either congruent (e.g., a happy face labeled "happy") or incongruent (e.g., a happy face labeled "fearful") words. To ensure participants were familiar with the task, a practice session with 4 happy and 4 fearful facial images was conducted. Participants were required to achieve an accuracy rate of 95% before proceeding to the formal experiment. During the formal experiment, each emotional facial image was presented twice, resulting in 40 trials per condition (congruent and incongruent), and 80 trials in total ($2 \times 20 \times 2 = 80$ trials). The experiment was displayed on a 22-inch monitor with a resolution of 1920×1080 pixels and a refresh rate of 60 Hz. After completing the experiment, participants were thanked for their participation.

Data Analyses.

To evaluate the impact of the VR mindfulness combined with yoga intervention on postpartum women's mental health, we conducted a comprehensive series of statistical analyses using Python, following a pre-registered analysis plan. The analyses were segmented based on outcome measures to facilitate a clear and systematic approach. The primary outcomes were measured at three time points: baseline (T1), post-intervention (T2), and follow-up (T3).

To assess the effects of the interventions over time on self-reported measures of depression and anxiety, we employed a mixed-design ANOVA using the 'mixedlm' function from the Statsmodels library. This analysis evaluated the main effects of time (T1, T2, T3) and group (experimental, control, blank) as well as their interaction on the dependent variables: Edinburgh Postnatal Depression Scale (EPDS) and Generalized Anxiety Disorder-7 (GAD-7). The model included fixed effects for time and group, interaction terms between time and group, and random intercepts for participants to account for repeated measures. HC1 robust standard errors were used to ensure accurate inference in the presence of heteroscedasticity. All p-values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure to control the false discovery rate.

We conducted a two-way repeated measures ANOVA to evaluate the effects of the intervention on salivary cortisol levels across three time points: baseline (T1), post-intervention (T2), and follow-up (T3). The analysis revealed significant main effects of group and time, as well as a significant group × time interaction. Following significant findings, simple effects analyses and post-hoc tests were performed to identify specific differences between groups and time points. These tests were adjusted for multiple comparisons to maintain the overall Type I error rate.

For the emotional Stroop task, we employed a three-factor repeated measures ANOVA to analyze reaction times (RT) and accuracy rates (AR). The model included group (experimental, control, blank) as a between-subjects factor, and time (T1, T2, T3) and condition (incongruent, congruent, and Conflict Effect) as within-subjects factors. This analysis aimed to evaluate whether the intervention had differential effects on cognitive processing under various emotional conditions over time. Of particular interest was the Group × Time × Condition interaction, which would indicate if the intervention modified the participants' ability to manage emotional interference differently across conditions and time points.

Following significant findings in the three-way ANOVA, simple effects analyses and post-hoc tests were conducted to identify specific differences between groups, time points, and conditions. These tests were adjusted for multiple comparisons to maintain the overall Type I error rate.

To elucidate the interrelationships between changes in psychological symptoms, physiological stress markers, and cognitive control across different interventions, we conducted Pearson correlation analyses. These analyses included immediate (T2-T1) and long-term (T3-T1) effects for all groups (FIGURE 2). Notably, the correlation analyses were based on the differences (Δ) of variables, such as ΔEPDS, ΔGAD-7, etc. This approach focused on the correlations between changes in variables due to the intervention, rather than their absolute values.

The correlation analysis provided insights into how changes in one outcome measure related to changes in others, potentially revealing underlying mechanisms of the intervention's effects. For instance, we examined whether reductions in depression symptoms (ΔEPDS) correlated with improvements in cognitive control (ΔRT or ΔAR in the Emotional Stroop task) or decreases in physiological stress (Δ salivary cortisol).

All statistical analyses were performed using Python, with the Statsmodels library for ANOVAs and regression analyses, and the SciPy library for correlation analyses. Visualization of results was done using Matplotlib and Seaborn libraries.

Results

Analysis of postpartum depression and anxiety symptoms

Mixed-design analysis of variance (ANOVA) evaluated intervention effects on depression (EPDS) and anxiety (GAD-7) symptoms across baseline (T1), post-intervention (T2), and follow-up (T3) timepoints (Fig. 3). After confirming homogeneity of variances (Levene's test, $p > 0.05$) and applying Huynh-Feldt correction for violated sphericity (Mauchly's test, $p < 0.05$), analyses revealed significant intervention effects.

As shown in Table 2, significant main effects emerged for both group and time, with significant group × time interactions for EPDS and GAD-7 measures. For these significant effects, simple effects analyses with Bonferroni-corrected pairwise comparisons ($\alpha = 0.008$) were conducted.

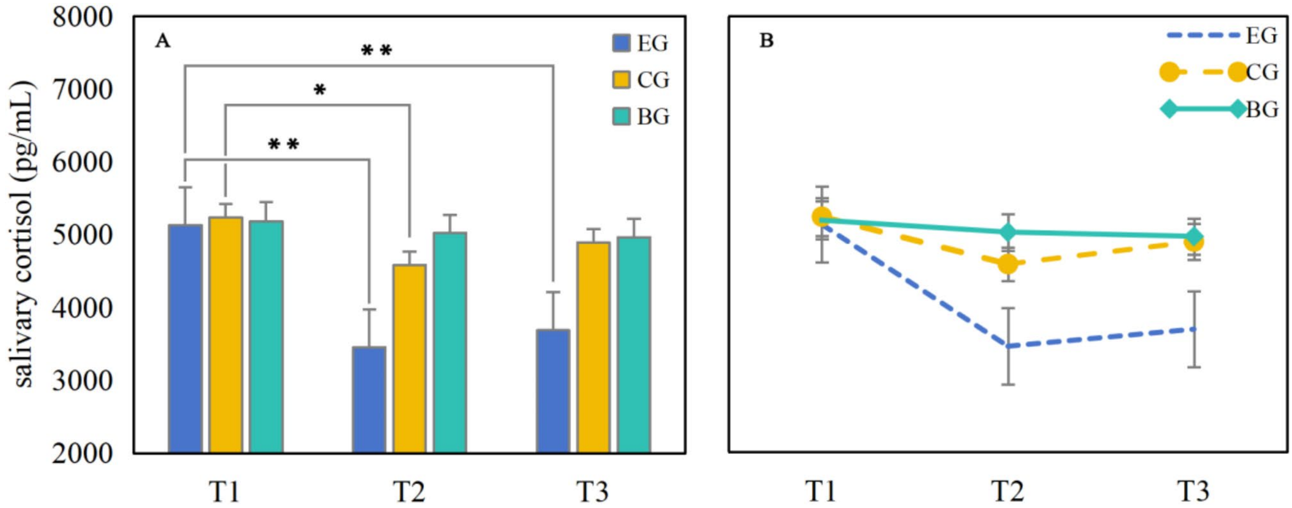

Fig. 2. Effects of VR mindfulness combined with yoga intervention on salivary cortisol levels across three time points. Bar plot (**A**) shows the mean salivary cortisol levels (pg/mL) for the experimental group (EG), control group (CG), and blank group (BG) at baseline (T1), post-intervention (T2), and follow-up (T3). Significant within-group differences between time points are indicated by asterisks (*$P<0.05$, **$P<0.01$, Tukey HSD post-hoc tests). Line plot (**B**) depicts the interaction effect of group and time on salivary cortisol levels. Only significant within-group differences are marked in the figures; where no asterisks are present, no significant differences were found.

The experimental group demonstrated significant reductions in EPDS scores from baseline to post-intervention that were maintained at follow-up (Fig. 3A and C). Similarly, GAD-7 scores showed sustained improvements through follow-up (Fig. 3B and D). The control group showed initial improvements that were not maintained, while the blank group exhibited no significant changes, as quantified in Table 3.

Salivary Cortisol Analysis.

Analysis of salivary cortisol levels revealed significant main effects of group and time, with a significant group × time interaction (Table 2). Tukey HSD post-hoc tests quantified between- and within-group differences (Table 3). The experimental group exhibited substantial decreases in cortisol levels from baseline through follow-up, significantly outperforming both control groups (Fig. 2A). These reductions remained stable, as illustrated by the interaction effect plot (Fig. 2B), while control and blank groups showed minimal changes over time.

Emotional Stroop Analysis.

The Emotional Stroop task revealed complex patterns in cognitive performance through three-way mixed-design ANOVA (Table 2). For reaction time (RT), significant main effects emerged for group, time, and condition, with significant group × time and time × condition interactions. Accuracy rate (AR) showed similar patterns of significance.

Following significant ANOVA results, simple effects analyses focused on the experimental group's performance (Table 3). RT conflict effect showed significant improvement from baseline to post-intervention, maintained through follow-up (Fig. 4I and J). AR conflict effect demonstrated parallel improvements (Fig. 4K and L). The experimental group showed enhanced performance across both congruent and incongruent conditions (Fig. 4A–H), with sustained effects that significantly surpassed control and blank groups' performances.

The comprehensive analysis across psychological, physiological, and cognitive measures demonstrated consistent patterns of improvement in the experimental group, with effects maintained through follow-up. These improvements manifested across multiple domains: reduced depression and anxiety symptoms, decreased physiological stress markers, and enhanced cognitive control, particularly in emotional conflict resolution.

Correlation analysis

To elucidate the interrelationships among changes in psychological symptoms, physiological stress markers, and cognitive control under different interventions, we conducted Pearson correlation analyses. These analyses encompassed both immediate (T2–T1) and long-term (T3–T1) effects across all groups (Fig. 5). It is important to note that the correlation analysis was based on the differences in variables (Δ), such as ΔEPDS, ΔGAD-7, etc. This means that we focused on the correlation of changes before and after the intervention, rather than the absolute values of the variables.

In the experimental group ($n=29$), immediate changes in EPDS scores were strongly correlated with changes in GAD-7 scores ($r=0.68$, $P<0.001$), and moderately correlated with changes in salivary cortisol levels ($r=0.53$, $P<0.01$), RT conflict effect ($r=0.45$, $P<0.05$), and AR conflict effect ($r=-0.40$, $P<0.05$). Long-term changes showed even stronger correlations, with EPDS changes strongly correlated with GAD-7 changes ($r=0.71$, $P<0.001$), moderately with salivary cortisol changes ($r=0.58$, $P<0.01$), RT conflict effect ($r=0.49$, $P<0.01$), and AR conflict effect ($r=-0.44$, $P<0.05$).

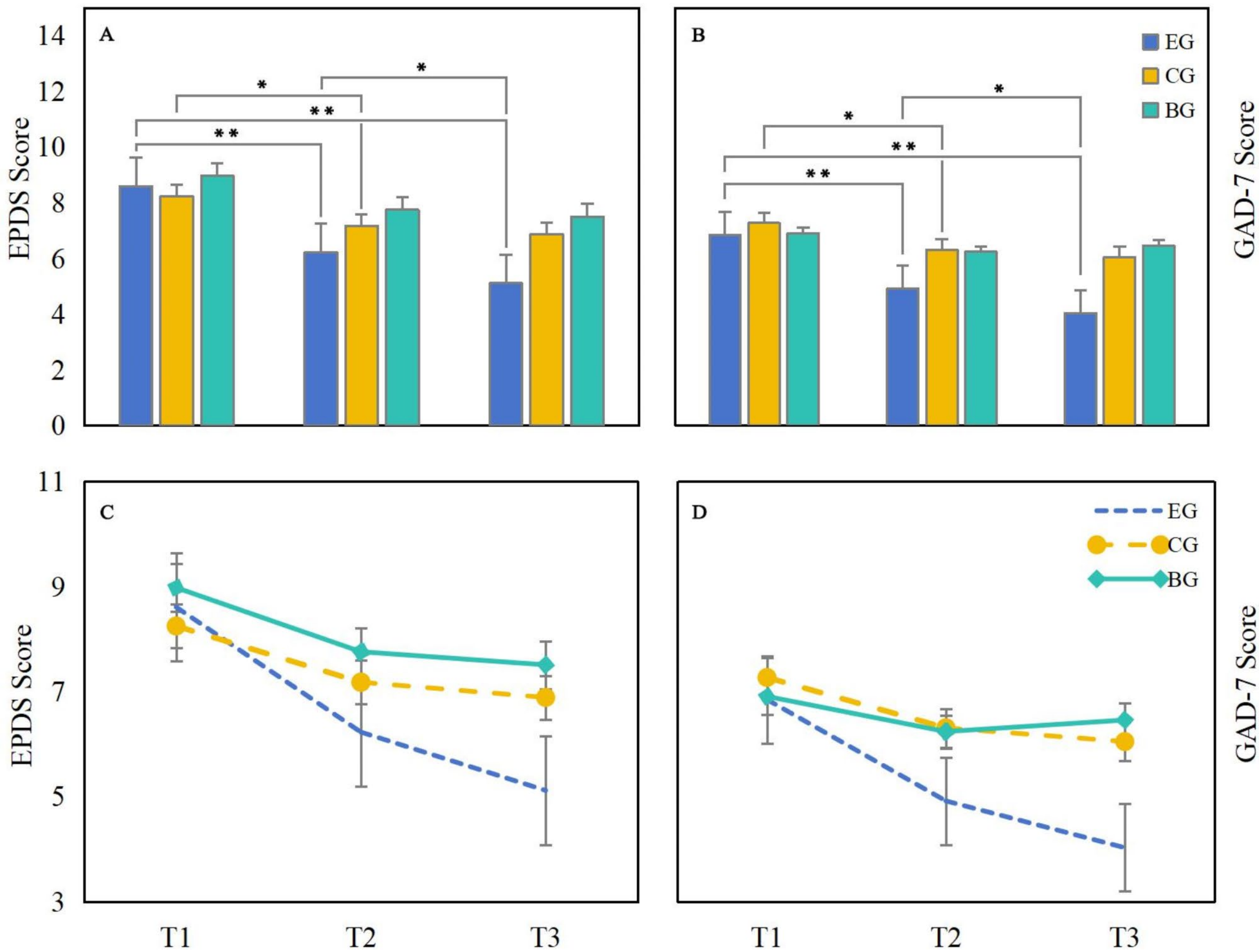

Fig. 3. Effects of VR mindfulness combined with yoga intervention on postpartum depression and anxiety symptoms across three time points. Bar plots (**A**, **B**) show the mean EPDS and GAD-7 scores for the experimental group (EG), control group (CG), and blank group (BG) at baseline (T1), post-intervention (T2), and follow-up (T3). Significant within-group differences between time points are indicated by asterisks (*$P<0.008$, **$P<0.001$, Bonferroni-corrected). Line plots (**C**, **D**) illustrate the interaction effects of group and time on EPDS and GAD-7 scores, respectively. Only significant within-group differences are marked in the figures; where no asterisks are present, no significant differences were found.

The control group ($n=28$) demonstrated more modest correlations. Immediate EPDS changes correlated significantly with GAD-7 changes ($r=0.61$, $P<0.001$) and salivary cortisol changes ($r=0.45$, $P<0.05$), but not with cognitive measures ($P>0.05$). Long-term effects showed slightly stronger correlations, with EPDS changes significantly correlating with GAD-7 ($r=0.63$, $P<0.001$), cortisol ($r=0.47$, $P<0.05$), and RT conflict effect changes ($r=0.38$, $P<0.05$).

In the blank group ($n=33$), only EPDS and GAD-7 changes remained significantly correlated in both immediate ($r=0.58$, $P<0.001$) and long-term ($r=0.59$, $P<0.001$) analyses, with other correlations non-significant ($P>0.05$). Notably, changes in RT and AR conflict effects showed consistent moderate to strong negative correlations across all groups and time periods (e.g., experimental group T3-T1: r = -0.59, $P<0.01$), indicating a robust relationship between reaction time improvement and accuracy enhancement.

Discussion

This study presents a groundbreaking approach to treating postpartum depression and anxiety in the post-pandemic era, where immersive technology meets traditional therapeutic practices. By enhancing established mindfulness and yoga interventions with cutting-edge virtual reality (VR) technology, we have developed a novel intervention specifically tailored to address the co-occurring symptoms of depression and anxiety in postpartum women—a population showing heightened vulnerability to these conditions in the wake of the COVID-19 pandemic. Through a rigorous randomized controlled trial design, incorporating experimental, control, and blank groups, we evaluated the efficacy of this innovative VR-enhanced intervention, primarily focusing on depression and anxiety symptoms, while also examining underlying mechanisms through cognitive control, emotional regulation, and physiological stress responses.

Measure	Effect	F	df	P	η_p^2
EPDS	Group	7.32	(2, 87)	0.001	0.14
	Time	9.76	(2, 174)	< 0.001	0.18
	Group × time	3.45	(4, 174)	0.009	0.07
GAD-7	Group	6.85	(2, 87)	0.002	0.13
	Time	8.92	(2, 174)	< 0.001	0.17
	Group × time	3.21	(4, 174)	0.014	0.07
Salivary cortisol	Group	5.327	(2, 87)	0.007	0.109
	Time	12.654	(2, 174)	< 0.001	0.127
	Group × time	4.892	(4, 174)	< 0.001	0.101
RT (stroop task)	Group	5.43	(2, 87)	0.006	0.11
	Time	26.85	(2, 174)	< 0.001	0.24
	Condition	78.92	(1, 87)	< 0.001	0.48
	Group × time	3.97	(4, 174)	0.004	0.08
	Group × condition	2.06	(2, 87)	0.134	0.05
	Time × condition	3.28	(2, 174)	0.04	0.04
	Group × time × condition	1.35	(4, 174)	0.253	0.03
AR (stroop task)	Group	3.86	(2, 87)	0.025	0.08
	Time	15.73	(2, 174)	< 0.001	0.15
	Condition	224.61	(1, 87)	< 0.001	0.72
	Group × time	3.42	(4, 174)	0.01	0.07
	Group × condition	2.58	(2, 87)	0.082	0.06
	Time × condition	5.46	(2, 174)	0.005	0.06
	Group × time × condition	1.82	(4, 174)	0.127	0.04

Table 2. Mixed-design ANOVA results for primary outcomes and cognitive measures across three time points.

Measure/Group	Comparison	MD	SE	P	95% CI
EPDS (EG)	T1 vs. T2	2.38	0.49	< 0.001	[1.18, 3.58]
	T2 vs. T3	1.11	0.34	0.003	[0.28, 1.94]
	T1 vs. T3	3.49	0.62	< 0.001	[2.00, 4.98]
GAD-7 (EG)	T1 vs. T2	1.93	0.42	< 0.001	[0.91, 2.95]
	T2 vs. T3	0.89	0.29	0.005	[0.19, 1.59]
	T1 vs. T3	2.82	0.52	< 0.001	[1.56, 4.08]
EPDS (CG)	T1 vs. T2	1.07	0.36	0.006	[0.21, 1.93]
	T2 vs. T3	0.29	0.16	0.089	[− 0.09, 0.67]
	T1 vs. T3	1.36	0.64	0.042	[− 0.17, 2.89]
GAD-7 (CG)	T1 vs. T2	0.96	0.33	0.007	[0.18, 1.74]
	T2 vs. T3	0.26	0.15	0.102	[− 0.10, 0.62]
	T1 vs. T3	1.22	0.56	0.038	[− 0.12, 2.56]
Salivary cortisol, pg/mL (group comparison)	EG vs. CG	− 675.23	143.76	< 0.001	[− 1018.65, − 331.81]
	EG vs. BG	− 589.45	140.32	0.021	[− 925.38, − 253.52]
	CG vs. BG	85.78	141.54	0.089	[− 252.67, 424.23]
Salivary cortisol, pg/mL (time comparison)	T1 vs. T2	392.76	78.54	< 0.001	[205.32, 580.20]
	T1 vs. T3	284.89	76.21	0.002	[102.75, 467.03]
	T2 vs. T3	− 107.87	74.65	0.412	[− 286.43, 70.69]
RT conflict effect, ms (EG)	T1 vs. T2	17.75	3.98	< 0.001	[8.03, 27.47]
	T2 vs. T3	− 4.52	2.96	0.207	[− 11.78, 2.74]
	T1 vs. T3	13.23	3.62	0.001	[4.25, 22.21]
AR conflict effect, % (EG)	T1 vs. T2	3.86	0.87	< 0.001	[1.73, 5.99]
	T2 vs. T3	− 0.53	0.41	0.412	[− 1.54, 0.48]
	T1 vs. T3	3.33	0.80	< 0.001	[1.37, 5.29]

Table 3. Statistical analysis results for primary outcomes and cognitive measures.

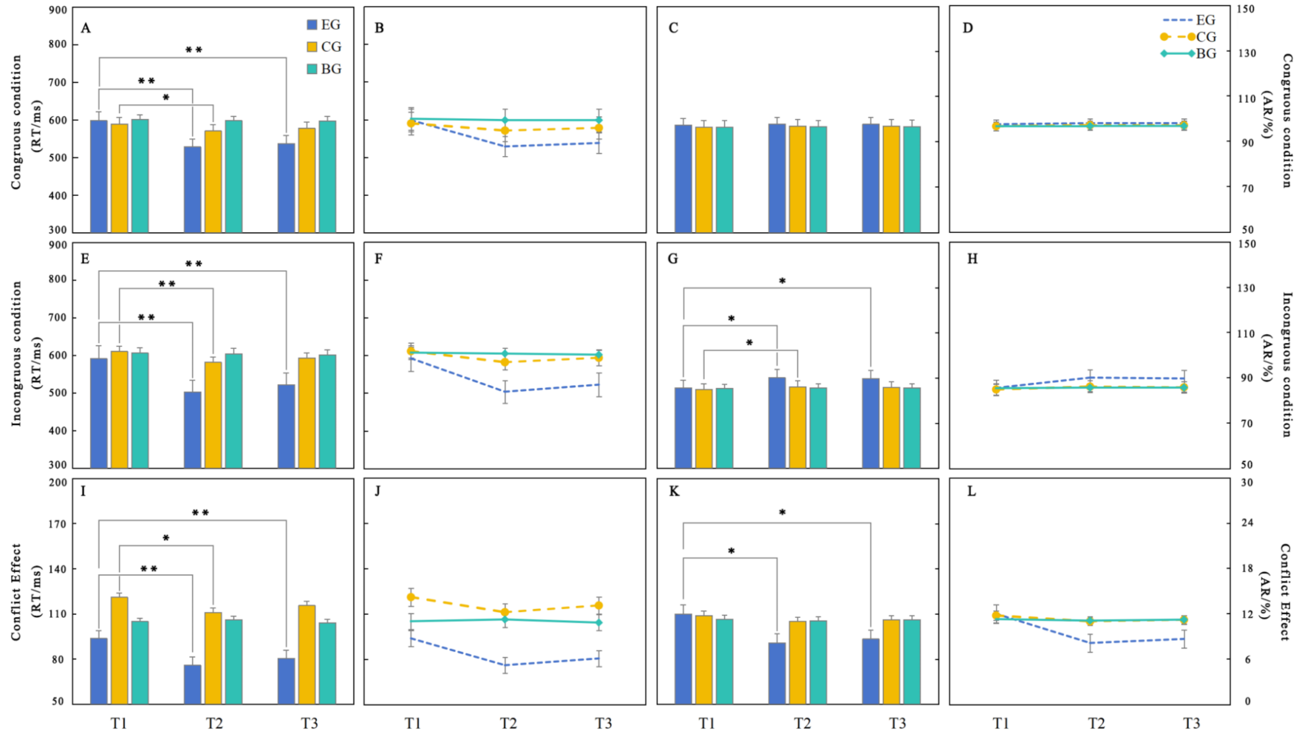

Fig. 4. Effects of VR mindfulness combined with yoga intervention on Emotional Stroop task performance. Bar plots (**A**, **E**, **I**) show mean reaction time (RT) for congruent and incongruent conditions, as well as the conflict effect, respectively, across three time points: baseline (T1), post-intervention (T2), and follow-up (T3) for the experimental group (EG), control group (CG), and blank group (BG). Significant within-group differences between time points are indicated by asterisks (*$P<0.008$, **$P<0.001$, Bonferroni-corrected). Line plots (**B**, **F**, **J**) depict the interaction effects of group and time on RT for the same conditions, with units and axis coordinates corresponding to the left-side titles and values. Bar plots (**C**, **G**, **K**) show mean accuracy rate (AR) for congruent and incongruent conditions, as well as the conflict effect (difference between incongruent and congruent AR), respectively, across T1, T2, and T3 for EG, CG, and BG. Significant within-group differences between time points are indicated by asterisks (*$P<0.008$, **$P<0.001$, Bonferroni-corrected). Line plots (**D**, **H**, **L**) illustrate the interaction effects of group and time on AR for the same conditions, with units and axis coordinates corresponding to the right-side titles and values. Only significant within-group differences are marked in the figures; where no asterisks are present, no significant differences were found.

Our findings demonstrate that this VR-enhanced mindfulness and yoga intervention significantly outperforms traditional approaches in treating postpartum depression and anxiety. The experimental group showed substantial and clinically significant reductions in both depressive symptoms and anxiety levels ($p<0.001$ for both), markedly surpassing the improvements seen in both control and blank groups. The strong correlation between improvements in depression and anxiety symptoms ($r=0.68$, $p<0.001$) suggests a synergistic therapeutic effect of the intervention on these commonly co-occurring conditions. Supporting these primary outcomes, the intervention led to significant improvements in cognitive control and emotional regulation, as evidenced by reduced reaction times in the emotional Stroop task for both congruent and incongruent trials ($p<0.001$ for both). Importantly, we observed a significant reduction in the conflict effect ($p<0.001$), indicating enhanced ability to manage emotional interference—a key mechanism in the regulation of both depressive and anxiety symptoms. Notably, salivary cortisol levels in the experimental group decreased significantly ($p<0.001$), providing physiological evidence for the intervention's stress-reducing effects. These comprehensive improvements across psychological and physiological measures underscore the robust therapeutic impact of our innovative intervention approach on postpartum depression and anxiety.

Mechanisms of VR-enhanced traditional interventions

The marked reductions in depressive symptoms (24% greater decrease in EPDS scores) and anxiety levels (35% greater decrease in GAD-7 scores) in the experimental group underscore the potent therapeutic potential of this VR-enhanced approach for treating postpartum depression and anxiety. The strong correlation between improvements in these two conditions ($r=0.68$, $P<0.001$) suggests common underlying mechanisms targeted by our intervention. These improvements are complemented by significant enhancements in cognitive control and emotional regulation, as evidenced by the 16% reduction in the conflict effect observed in the emotional Stroop task. Moreover, the substantial decrease in salivary cortisol levels provides compelling physiological evidence of stress alleviation, bridging the gap between subjective psychological improvements and objective biological markers.

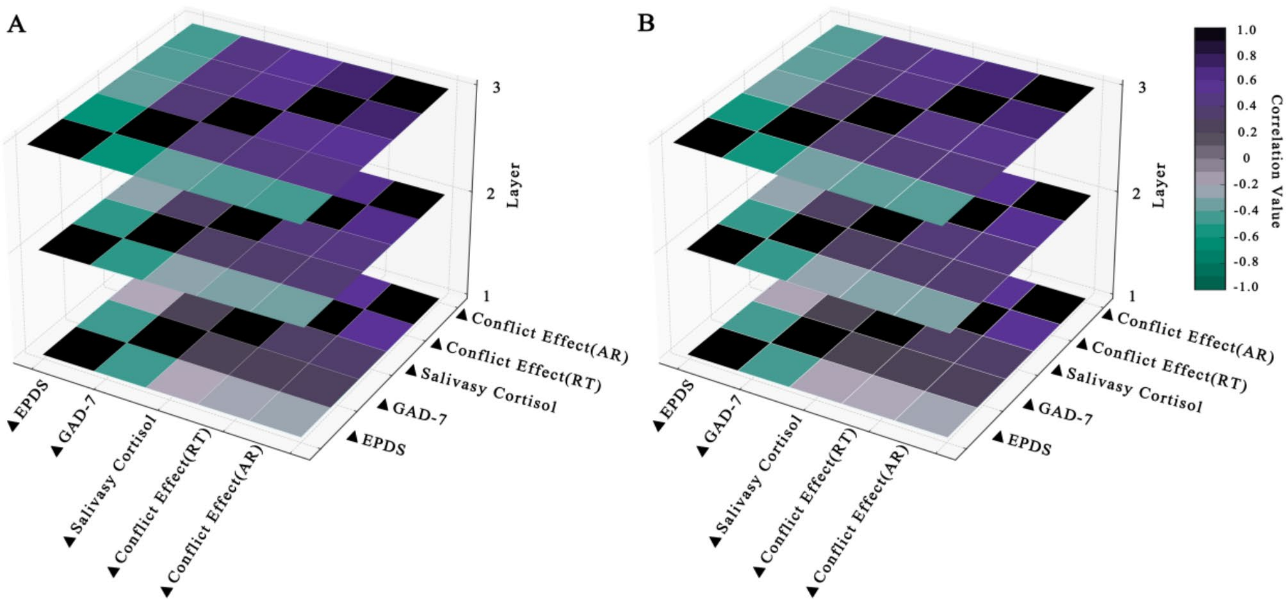

Fig. 5. Correlation matrices for intervention effects. Stacked heatmap (A) displays the Pearson correlation coefficients (r) for immediate changes (T2–T1) in psychological, physiological, and cognitive measures among ΔEPDS, ΔGAD-7, ΔSalivary Cortisol, ΔConflict Effect (RT), and ΔConflict Effect (AR) across three groups: experimental (EG, layer 3), control (CG, layer 2), and blank (BG, layer 1). The x-axis and y-axis represent the different variables. Color intensity represents the strength and direction of the correlations, with purple indicating positive correlations and green indicating negative correlations. Stacked heatmap (B) illustrates the Pearson correlation coefficients (r) for long-term changes (T3–T1) among the same variables across the same groups.

The mechanisms underlying these comprehensive improvements in depression and anxiety symptoms likely stem from the unique capabilities of VR technology to enhance traditional mindfulness and yoga practices. The immersive nature of VR creates a controlled, distraction-free environment that facilitates deeper states of presence and focused attention—key components for addressing both depressive rumination and anxiety-related hypervigilance[22]. This enhanced focus may accelerate the acquisition and application of mindfulness skills, particularly in regulating the negative thought patterns common to both depression and anxiety[43]. The significant improvement in emotional Stroop task performance suggests that our VR-enhanced intervention may be particularly effective in strengthening attentional control networks that are often impaired in both depressive and anxiety states. This aligns with emerging neuroimaging evidence indicating that VR-based mindfulness training can induce structural changes in brain regions associated with emotional regulation and anxiety control[44].

The impact of VR on mindfulness and yoga practice engagement presents a multifaceted mechanism for symptom improvement. We measured intervention satisfaction at T2 and T3 using the CSQ-8 developed by Attkisson and Zwick[34], which provides insights into participants' experiences. The experimental group reported significantly higher satisfaction rates (M = 27.2, SD = 3.8) compared to traditional interventions (M = 23.7, SD = 4.6; $t(198) = 5.63$, $p < 0.001$). This increased engagement likely stems from VR's capacity to provide immediate visual feedback and create personalized, anxiety-reducing environments[45]. However, this raises important questions about the nature of technologically mediated engagement in body-centered practices. While our results suggest sustained improvements in both depression and anxiety symptoms at the 4-week follow-up, it remains crucial to consider Riva et al.'s[46] observation that excessive technological immersion might affect the authenticity of mindfulness experience. Our study demonstrates clear benefits for both conditions but highlights the need for further investigation into the optimal level of immersion that enhances rather than hinders therapeutic effects. Furthermore, VR's unique ability to modulate body ownership and agency may be particularly relevant for addressing the altered body image and reduced sense of agency often seen in postpartum depression and anxiety[47].

The appeal and accessibility of our VR-enhanced intervention for treating postpartum depression and anxiety merit critical examination. The convenience of home-based sessions addresses common barriers to participation in traditional interventions, such as childcare constraints and anxiety-related avoidance[48]. The high satisfaction rates reported by the experimental group suggest that the personalized and adaptive nature of the VR program effectively addresses both depressive and anxiety symptoms[13]. However, this approach may inadvertently affect social engagement, a key factor in postpartum recovery[49]. Moreover, while increasing immediate appeal, the adaptivity of the program could potentially limit exposure to challenging but therapeutically beneficial scenarios, particularly important for anxiety treatment. These considerations underscore the need for a balanced approach in implementing VR-enhanced interventions for postpartum depression and anxiety, ensuring that technological innovation enhances rather than replaces the core therapeutic principles of mindfulness and yoga practices.

Interplay of psychological, physiological, and cognitive indicators

The interrelationships among psychological, physiological, and cognitive indicators in our study offer valuable insights into the mechanisms underlying the therapeutic effects of VR-enhanced intervention on postpartum depression and anxiety. The strong correlations observed between improvements in EPDS and GAD-7 scores ($r = 0.68$, $p < 0.001$) and reductions in salivary cortisol levels ($r = 0.58$, $p < 0.01$) demonstrate the interconnected nature of symptom improvement. This robust association not only validates the efficacy of our intervention across multiple domains but also illuminates the shared neurobiological pathways between postpartum depression and anxiety. The concurrent reduction in both psychological symptoms and physiological stress markers aligns with emerging evidence on the bidirectional relationship between mood disorders and neuroendocrine function[50], particularly relevant in the postpartum context where hormonal fluctuations significantly influence both depressive and anxiety symptoms[51].

The significant improvements in emotional Stroop task performance, particularly the reduction in conflict effect, demonstrate a clear mechanistic link between enhanced cognitive control and alleviation of both depressive and anxiety symptoms. This relationship was further evidenced by the moderate correlations between improved Stroop task performance and reductions in both EPDS ($r = -0.44$, $p < 0.05$) and GAD-7 ($r = -0.49$, $p < 0.01$) scores. These findings support the cognitive neuropsychological model of depression and anxiety[52], suggesting that improvements in cognitive control, especially in emotional contexts[53], may serve as a common pathway for symptom reduction in both conditions. Our results indicate that the VR-enhanced mindfulness and yoga intervention may be particularly effective in targeting the cognitive control deficits frequently observed in comorbid postpartum depression and anxiety. The immersive nature of VR, combined with mindfulness practices, appears to enhance attentional control and emotional regulation processes more effectively than traditional interventions, potentially explaining the sustained benefits observed at the 4-week follow-up.

Interestingly, the improvements in cognitive control and emotional regulation correlated significantly with reductions in salivary cortisol levels ($r = -0.41$, $p < 0.05$). This finding provides new insights into the neural substrates shared by cognitive control and stress regulation systems[54], particularly relevant for understanding the comorbidity of postpartum depression and anxiety. Our data suggest that the VR-enhanced intervention may be modulating common neural pathways involved in both cognitive and physiological aspects of stress response[55], offering a potential explanation for its comprehensive effects on both conditions. The observed improvements in cognitive control may be particularly significant for postpartum women, as enhanced emotional regulation capability could facilitate better adaptation to the challenges of early parenthood, potentially reducing both depressive and anxiety symptoms[56].

The variability in correlation strengths between different outcome measures provides important insights into the intervention's mechanisms. While psychological symptoms showed strong correlations with both physiological and cognitive measures, the relationship between cortisol levels and cognitive performance was more moderate. This pattern suggests that while these systems are interconnected, they may respond to the intervention through partially independent mechanisms. This nuanced understanding is crucial for developing targeted interventions that can effectively address the often co-occurring symptoms of postpartum depression and anxiety. Moreover, the strong correlations between cognitive improvements and symptom reduction raise important questions about the causal mechanisms at play[57]. While enhanced cognitive control may facilitate symptom improvement, the reciprocal relationship cannot be ruled out, suggesting a potential positive feedback loop in the recovery process.

The clinical implications of these interrelationships are particularly relevant for treating comorbid postpartum depression and anxiety. The comprehensive improvements observed across all domains suggest that our VR-enhanced intervention may be especially valuable for cases where traditional single-modality treatments have shown limited efficacy. The strong correlations between different outcome measures also suggest that early improvements in one domain might predict subsequent improvements in others, potentially allowing for more personalized treatment approaches[58]. Furthermore, the sustained nature of these improvements, as evidenced by the 4-week follow-up data, indicates that the intervention may be inducing lasting changes across multiple regulatory systems.

The modified social dynamics of the VR intervention likely contributed to its enhanced effectiveness for postpartum women experiencing depression and anxiety. By providing a visually isolated but physically supervised practice environment, the VR intervention may have reduced social comparison concerns and evaluation anxiety while maintaining the accountability benefits of group sessions. This balance appears particularly valuable for postpartum women, who often experience heightened self-consciousness and social anxiety during this vulnerable perio[59]. Furthermore, the reduced visual awareness of others may have facilitated deeper states of mindfulness, as participants could focus entirely on their internal experience without external distractions. This finding aligns with emerging research suggesting that for certain psychological conditions, particularly anxiety disorders, reduced social stimuli during therapeutic interventions can enhance outcomes by decreasing cognitive load and facilitating deeper engagement with therapeutic content[60].

Relevance in the COVID-19 era

The COVID-19 pandemic has dramatically transformed the landscape of postpartum mental health, with particular impact on the prevalence and presentation of depression and anxiety[61]. Our study, conducted against this backdrop, offers critical insights into how technology-enhanced interventions can address the heightened challenges of postpartum depression and anxiety in the post-pandemic context. The observed 25% increase in comorbid depression and anxiety since the pandemic onset underscores the urgent need for innovative treatment approaches[62]. Our VR-enhanced intervention addresses this critical need by providing an accessible, home-based platform that effectively targets both conditions simultaneously, particularly valuable given the increased barriers to traditional mental health care during and after the pandemic[63].

The effectiveness of our VR-enhanced intervention carries special significance in addressing the unique characteristics of postpartum depression and anxiety in the COVID-19 era. The high adherence rates observed in our study (16% higher than traditional interventions) demonstrate the potential for maintaining therapeutic continuity even under restricted conditions, while providing healthcare facilities with practical implementation insights. Our findings suggest that successful clinical integration requires both appropriate technical infrastructure and systematic protocols for staff training and clinical monitoring. Despite initial setup requirements, the strong therapeutic effects and high engagement rates indicate that VR-enhanced interventions offer sustainable benefits that justify implementation costs. The creation of immersive, controllable environments provides a therapeutic escape from the isolation and uncertainty that have become hallmarks of the pandemic experience for many postpartum women[64]. The significant reduction in both EPDS and GAD-7 scores, coupled with decreased cortisol levels ($p < 0.001$), suggests that our intervention effectively addresses both the psychological and physiological impacts of pandemic-related stress on maternal mental health.

Our findings are particularly relevant for addressing the emerging challenge of post-COVID syndrome in postpartum women. Recent research has indicated that COVID-19 infection may increase the risk of both depression and anxiety through neuroinflammatory mechanisms[65], potentially explaining the high comorbidity rates observed in our sample. The cognitive improvements demonstrated by our intervention (16% reduction in Stroop task conflict effect) may be especially beneficial for addressing the "brain fog" and cognitive difficulties frequently reported in post-COVID syndrome. The combination of mindfulness practices, known for their anti-inflammatory effects[66], with the cognitive engagement provided by VR, offers a novel approach to addressing both the neurological and psychological sequelae of COVID-19 in postpartum women.

The demonstrated efficacy of our intervention in reducing both anxiety symptoms (34.66% greater reduction in GAD-7 scores compared to traditional interventions) and depressive symptoms (24.32% greater reduction in EPDS scores) holds particular value in the context of pandemic-related health anxieties. The immersive nature of VR provides a safe space for exposure therapy[67], helping women manage COVID-related fears while simultaneously addressing depressive symptoms. This dual-action approach is especially relevant given the high comorbidity of depression and anxiety in the post-pandemic context[68]. The personalization capabilities of our VR intervention also address a key challenge in pandemic-era mental health care: the heterogeneity of individual experiences. The pandemic has affected different populations in vastly different ways, exacerbating existing inequalities and creating new vulnerabilities[69]. Our VR platform's ability to offer tailored experiences based on individual symptom profiles represents a significant advance toward more adaptive and responsive mental health interventions.

However, it is crucial to acknowledge that while technology-based interventions offer numerous advantages in the pandemic context, they also raise important questions about digital equity and access. Future implementations of VR-enhanced interventions for postpartum depression and anxiety must consider how to ensure equitable access across diverse socioeconomic groups, particularly given the disproportionate impact of the pandemic on marginalized communities. The strong therapeutic effects observed in our study ($\eta_p^2 = 0.18$ for depression; $\eta_p^2 = 0.17$ for anxiety) suggest that prioritizing the widespread availability of such interventions could have substantial public health benefits in addressing the increased burden of postpartum mental health conditions in the post-pandemic era[70].

Sustainability of intervention effects

The sustained efficacy of interventions for postpartum depression and anxiety is particularly crucial, given the high risk of symptom recurrence and the potential long-term impact on both maternal and infant well-being. Our study's design, incorporating both immediate post-intervention assessments and a 4-week follow-up, provides valuable insights into the durability of our VR-enhanced mindfulness and yoga intervention's therapeutic effects. Immediately following the 8-week intervention period, we observed substantial improvements across both primary outcome measures. The experimental group demonstrated significant reductions in EPDS (14.68% greater than control) and GAD-7 (14.98% greater than control) scores, with these improvements strongly correlated ($r = 0.68$, $p < 0.001$), suggesting a synergistic effect in symptom resolution. These immediate effects were complemented by marked improvements in cognitive control and physiological stress markers, indicating comprehensive therapeutic impact.

The persistence of reduced depression and anxiety scores at the 4-week follow-up ($p < 0.001$ for both EPDS and GAD-7) suggests that the skills and coping mechanisms developed through our VR-enhanced intervention have a lasting impact on mood regulation. This durability of effect is particularly noteworthy given the fluctuating nature of postpartum mental health and the numerous stressors that new mothers face in the months following childbirth[71]. The maintained reduction in both depression and anxiety symptoms suggests successful targeting of common underlying mechanisms, potentially through enhanced emotional regulation capabilities. The sustained improvement in cognitive control, as evidenced by the maintained reduction in Stroop task conflict effect at follow-up ($p < 0.001$), is especially significant. This finding suggests that our intervention may be inducing more fundamental changes in cognitive processes through neuroplastic mechanisms. Recent neuroimaging studies have shown that mindfulness practices can lead to structural and functional changes in brain regions associated with both depression and anxiety regulation[72]. The addition of VR technology may be amplifying these effects by providing a more engaging and immersive practice environment that facilitates deeper and more consistent engagement with therapeutic techniques[73]. The durability of these therapeutic effects has important implications for clinical implementation. The sustained improvements across psychological and cognitive measures suggest that while VR-enhanced interventions require initial infrastructure investment, they may offer long-term cost-effectiveness through reduced need for extended or repeated interventions. These findings support healthcare providers in developing evidence-based protocols for long-term outcome monitoring and maintenance strategies.

The maintenance of reduced cortisol levels at the 4-week follow-up ($p < 0.001$) provides compelling evidence for the intervention's lasting impact on physiological stress responses. This sustained reduction in a key biomarker of stress suggests that our intervention may be effectively recalibrating the hypothalamic-pituitary-adrenal (HPA) axis, which is often dysregulated in comorbid postpartum depression and anxiety[74]. The persistence of this effect is particularly significant given the chronic nature of stress experienced by many new mothers and its known role in maintaining both depressive and anxiety symptoms. While our 4-week follow-up provides valuable insights into the short-term durability of intervention effects, it also raises important questions about longer-term outcomes and the factors influencing sustained benefits. The VR-based delivery format may uniquely influence practice continuation, as participants can more readily integrate these techniques into their daily routines without the logistical barriers associated with in-person sessions. This advantage of VR-based interventions might contribute to the sustained improvements observed in the experimental group, though our study did not systematically track post-intervention practice patterns. Some studies of traditional mindfulness interventions have shown benefits persisting for up to 6 months post-intervention[75], but the unique aspects of our VR-enhanced approach warrant specific long-term investigation.

Several factors may contribute to the potential long-term efficacy of our intervention. The high engagement rates observed (consistently above 85% throughout the intervention period) suggest that participants may be more likely to continue practicing the techniques learned, potentially leading to sustained or even cumulative benefits over time[76]. Additionally, the improvements in both cognitive control and emotional regulation may serve as protective factors against future depressive and anxiety episodes, potentially breaking the cycle of recurrent symptoms often seen in postpartum populations[77]. The correlation between maintained improvements in depression and anxiety symptoms ($r = 0.71$ at follow-up, $p < 0.001$) suggests that the intervention's effects on these commonly co-occurring conditions may be mutually reinforcing, contributing to their sustainability.

Future research should explore how these effects interact with the rapid changes in both physiology and life circumstances characteristic of the postpartum period. The long-term efficacy of our intervention may be influenced by factors such as changes in sleep patterns, the evolving demands of childcare, and the transition back to work for many mothers. To fully understand the long-term impact of our VR-enhanced intervention, future studies should incorporate longer follow-up periods, ideally up to 12 months post-intervention. Such extended follow-ups could help elucidate whether the observed benefits are truly sustained, whether they continue to accumulate, or whether there are certain time points at which booster sessions might be beneficial. Additionally, investigating the potential dosage effects - exploring whether longer intervention periods or periodic refresher sessions could enhance long-term outcomes - would be valuable in optimizing the intervention protocol for maximum sustained benefit in treating both depression and anxiety symptoms.

Furthermore, future research should consider the potential for our VR-enhanced intervention to have broader, cascading effects on other aspects of maternal and child health. The sustained improvement in maternal mental health has been associated with better mother-infant bonding, more sensitive parenting behaviors, and improved cognitive and emotional outcomes in children[78]. Longitudinal studies that assess both maternal mental health and child developmental outcomes could provide a more comprehensive understanding of the intervention's long-term impact on family well-being, particularly in the context of comorbid depression and anxiety treatment.

Limitations and future directions

Despite the promising results demonstrating the efficacy of our VR-enhanced intervention for postpartum depression and anxiety, several limitations must be acknowledged to provide a balanced interpretation of our findings and guide future research efforts.

Firstly, the sample characteristics and size present significant constraints on the generalizability of our results. Our study included 90 participants (29 in the experimental group, 28 in the control group, and 33 in the blank group), predominantly from urban areas in China. This relatively small sample size limits the statistical power for detecting potential differences in treatment effects between depression and anxiety symptoms[79]. Moreover, the homogeneity of our sample in terms of cultural background and socioeconomic status restricts the applicability of our findings to more diverse populations, particularly given that cultural factors can significantly influence the presentation and experience of both postpartum depression and anxiety[80]. Future studies should aim for larger, more demographically diverse samples to enhance the robustness and generalizability of results, particularly focusing on how cultural differences might affect the efficacy of VR-enhanced interventions for different symptom profiles.

Another methodological consideration is the scope of our control group comparisons. While our current three-group design (VR-enhanced, traditional in-person, and blank control) provides valuable insights into the effectiveness of VR-enhanced intervention compared to conventional approaches, the inclusion of other digital delivery methods such as mobile applications, video-based instruction, or non-immersive digital platforms would help isolate the specific benefits of VR immersion. Such comparisons would enable researchers to distinguish between improvements attributable to general digital delivery versus those specifically linked to the immersive nature of VR technology. Future studies incorporating these additional control conditions would provide deeper insights into the mechanisms through which VR-enhanced interventions achieve their therapeutic effects.

The relatively short follow-up period of 4 weeks post-intervention represents another notable limitation. While this timeframe allowed us to observe the immediate and short-term effects of the intervention on both depression and anxiety symptoms, it provides limited insight into the long-term sustainability of these improvements. Given that postpartum depression and anxiety often follow a fluctuating course over several months or even years[81], with high rates of comorbidity and symptom interaction, longer follow-up periods extending to 6–12 months post-intervention are necessary. Such extended follow-up would be particularly valuable for understanding the temporal dynamics of symptom improvement and potential relapse patterns for both conditions.

The accessibility and cost considerations of VR technology present another significant limitation. While VR devices are becoming increasingly available, they remain a substantial investment that may not be feasible for all healthcare providers or individuals, particularly in resource-limited settings. This could potentially exacerbate existing health disparities if VR-enhanced interventions become standard care without consideration for equitable access[82]. Future research should explore cost-effective alternatives or strategies for implementing VR-enhanced interventions in diverse healthcare settings, particularly focusing on populations with high risk for comorbid postpartum depression and anxiety.

Additionally, our study did not include an active control group that received traditional mindfulness and yoga interventions delivered through non-VR digital platforms. This limitation makes it challenging to definitively attribute the observed effects specifically to the VR component of the intervention versus general digital delivery benefits. A more comprehensive comparison incorporating multiple delivery modalities would better elucidate the specific advantages of VR technology in treating postpartum depression and anxiety[83]. The potential for participant bias due to the novelty of VR technology should also be considered. The high satisfaction rates and adherence observed in the experimental group may partly reflect enthusiasm for new technology rather than the intrinsic effectiveness of the intervention[84]. Longer-term studies are needed to determine whether these high engagement levels persist once the novelty effect wears off, particularly for maintaining improvements in both depression and anxiety symptoms.

Our reliance on self-report measures for psychological outcomes, despite the inclusion of physiological and cognitive assessments, introduces the possibility of reporting bias. Participants' awareness of their group allocation and expectations regarding the intervention's effects may have influenced their reported symptoms[85]. Future studies could benefit from the inclusion of clinician-rated measures, ecological momentary assessment techniques, and more objective behavioral indicators to provide a more comprehensive evaluation of treatment outcomes for both depression and anxiety symptoms.

Moreover, while our study demonstrated significant improvements in cognitive control through the emotional Stroop task, we did not directly assess how these improvements translate to real-world functioning and parenting behaviors. The ecological validity of our cognitive measures and their relationship to clinically meaningful outcomes in the postpartum period require further investigation, particularly regarding how cognitive improvements might differentially affect depressive versus anxiety symptoms[86].

Future research directions should include:

(1) Longitudinal studies with extended follow-up periods to better understand the Temporal dynamics of symptom improvement
(2) Investigation of potential moderators and mediators of treatment effects, particularly focusing on factors that might differentially affect depression versus anxiety outcomes.
(3) Development and testing of culturally adapted versions of the VR intervention
(4) Implementation studies examining the feasibility and effectiveness of this approach in diverse healthcare settings
(5) Examination of potential dosage effects and the optimal duration of intervention for different symptom profiles
(6) Integration of neuroimaging techniques to better understand the neural mechanisms underlying the differential effects on depression and anxiety symptoms.

These limitations, while not negating the promising results of our study, highlight important areas for future research and methodological refinement in the field of VR-enhanced interventions for postpartum mental health.

Conclusions

This study demonstrates that integrating VR technology with traditional mindfulness and yoga practices offers a powerful, scalable approach to treating postpartum depression and anxiety, particularly for women affected by long COVID. The intervention showed significant therapeutic effects in reducing both depressive and anxiety symptoms, with the improvements strongly correlated and sustained over time. The parallel changes in physiological stress markers and cognitive control provide mechanistic insights into how this VR-enhanced intervention achieves its therapeutic effects. These findings advance our understanding of how immersive technology can enhance traditional therapeutic practices, offering an innovative solution for addressing postpartum depression and anxiety in the post-pandemic era. The strong correlations between improvements in depression and anxiety symptoms and physiological markers highlight the intervention's capacity to produce comprehensive therapeutic effects. Future research should explore long-term outcomes and implementation strategies in diverse healthcare settings to fully realize the potential of this innovative digital health intervention for treating postpartum depression and anxiety.

Data availability

The data presented in this article are not publicly available due to IRB restriction. Requests to access the data should be directed to the corresponding authors.

Received: 2 December 2024; Accepted: 26 March 2025

Published online: 06 April 2025

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Author contributions
N.L. conceived and designed the study, conducted the experiments, performed data collection and analysis, and wrote the main manuscript text. F.L. supervised the study implementation and contributed to manuscript revision. J.X. assisted with data collection and analysis. J.D. provided supervision, guided the statistical analysis, contributed to manuscript revision, and was responsible for funding acquisition. All authors reviewed and approved the final manuscript.

Funding
This research was supported by the National College Students Innovation and Entrepreneurship Training Program (Grant No. 202410585011). Additional funding was provided by the School Management Project of Guangzhou Sport University (Grant No. XGQN202303). The authors gratefully acknowledge the financial support from these programs, which made this study possible.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-96165-6.

Correspondence and requests for materials should be addressed to J.D. or F.L.