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Virtual Reality (VR) for Mental Skills Training in Elite Athletes: A Quasi-Experimental Study

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ABSTRACT

This Quasi-Experimental Study examined the efficacy of virtual reality (VR)-enhanced mental skills training compared to traditional methods in improving psychological resilience, physiological regulation, and sport-specific performance among elite athletes. Eighty elite athletes (40 male, 40 female) from football, basketball, swimming, and track and field were randomly assigned to either a VR training group (n=40) or a traditional mental skills training group (n=40). The VR group completed six weeks of immersive, biofeedback-assisted sessions using the Meta Quest Pro headset with sport-specific scenarios, while the control group received conventional mental training. Psychological (SMTQ, CSAI-2R), physiological (HRV, EDA), and performance metrics were assessed at baseline, post-intervention, and three-month follow-up. The VR group demonstrated significantly greater improvements in mental toughness (28.6% vs. 12.4%, $p < 0.001$), faster autonomic recovery (40% reduction in stress recovery time, $p = 0.003$), and enhanced decision-making under pressure (23% faster correct responses, $p < 0.001$) compared to controls. Team sport athletes showed larger benefits than individual sport athletes ($p = 0.02$), and effects were maintained at follow-up with minimal decay (<5%). VR-based mental training outperforms traditional methods, particularly when integrated with biofeedback and sport-specific simulations. These findings support VR as a transformative tool for elite athlete preparation, offering scalable, data-driven psychological training with lasting effects.

Keywords: *virtual reality, mental skills training, elite athletes, biofeedback, sport psychology.*

1. Introduction

In recent years, virtual reality (VR) technology has emerged as a transformative tool in sports science, offering unprecedented opportunities for enhancing mental skills, physical performance, and injury rehabilitation across a wide range of athletic disciplines (Akbaş et al., 2019; Richlan et al., 2023). By immersing athletes in controlled, yet highly realistic, sport-specific scenarios, VR enables the replication of high-pressure competitive environments while providing precise, real-time performance feedback. This capacity to simulate the perceptual, cognitive, and emotional demands of competition aligns closely with contemporary theories of skill acquisition, which emphasize the importance of contextually rich, representative learning conditions (Gray, 2017; Pagé et al., 2019). While the application of VR in sports was initially concentrated in motor learning and perceptual training, recent advances in hardware fidelity, motion tracking, and haptic feedback have expanded its potential into the domain of psychological skills training and cognitive performance optimization (Arthur et al., 2023; Egiziano et al., 2025).

The integration of VR into sports training is underpinned by a growing body of research that demonstrates its efficacy in eliciting neuroplastic changes and improving sport-relevant cognitive processes (Drigas & Sideraki, 2024; Gangemi et al., 2023). Neuroimaging and neurophysiological studies have shown that VR training can activate neural networks associated with visuospatial processing, motor planning, and decision-making to a degree comparable with, and in some cases exceeding, real-world practice (Imperiali et al., 2025; Kisker et al., 2025). For instance, controlled investigations have found that VR-based simulations can significantly reduce decision latency and improve accuracy in time-critical sporting tasks, outcomes attributed to the technology's ability to provide immediate feedback and adaptive difficulty scaling (Jia et al., 2024; Zhu et al., 2024). These findings are further reinforced by meta-analytic evidence indicating that perceptual–cognitive training delivered through immersive VR can enhance anticipation and decision-making skills in team sports to a degree surpassing traditional video-based or 2D simulation methods (Witte et al., 2025; Zhu et al., 2024).

Beyond cognitive benefits, VR offers unique advantages for the development of mental skills critical to high-level performance, such as emotional regulation, focus, and resilience under pressure (Corrado et al., 2024; Trpkovici et al., 2025). Unlike conventional mental skills training methods—often reliant on guided imagery or abstract visualization—VR immerses athletes in vivid, multisensory contexts that closely replicate the psychological and environmental stressors of competition. This immersion can strengthen the transfer of learned coping strategies to actual competitive situations (Bedir & Erhan, 2021; Bedir et al., 2025). Furthermore, VR allows for the systematic manipulation of stress variables—such as crowd noise, time pressure, or opponent behavior—in a safe, repeatable manner, providing a platform for graduated exposure and "stress inoculation" (Akbaş et al., 2019; Lemmens, 2023).

An emerging and particularly impactful direction involves the integration of VR with biofeedback mechanisms, enabling athletes to monitor and modulate physiological responses in real time (Demeco et al., 2024; Harris et al., 2020). Heart rate variability (HRV), electrodermal activity (EDA), and other autonomic markers can be displayed within the VR environment, creating closed-loop learning systems that reinforce self-regulation skills essential for optimal performance (Halkiopoulos & Gkintoni, 2025; Weiß et al., 2024). Such approaches are supported by findings in both clinical and performance domains, where coupling VR immersion with physiological monitoring has been shown to accelerate recovery from stress and enhance readiness for competition (Huygelier et al., 2021; Khan et al., 2024). In football, for example, VR-based rehabilitation protocols have demonstrated efficacy not only in physical recovery but also in maintaining decision-making sharpness during injury downtime (Demeco et al., 2024; Manzi et al., 2025).

The adaptability of VR also lends itself to sport-specific customization, a factor increasingly recognized as essential for maximizing transfer of training effects (Catania et al., 2023; Mao et al., 2024). Team sports, with their complex, dynamic, and socially interactive environments, appear particularly well-suited to VR-based cognitive training (Jia et al., 2024; Mao et al., 2024). Simulations can incorporate interactive avatars, variable tactical formations, and unpredictable opponent behaviors, replicating the perceptual–cognitive demands of real play (Pagé et al., 2019; Zhu et al., 2024). In contrast, individual sports may benefit more from VR scenarios that emphasize rhythm, precision, and kinaesthetic awareness, often combined with mental rehearsal techniques that target performance consistency (Bedir & Erhan, 2021; Imperiali et al., 2025).

Recent research has also explored the potential of VR to support emotional and cognitive recovery following neurological or psychological setbacks, including post-stroke rehabilitation (Khan et al., 2024; Khan et al., 2023), anxiety management in athletes (Trpkovici et al., 2025), and the mitigation of performance anxiety in high-stakes events (Brizzi et al., 2025; Huang et al., 2022). The immersive and controllable nature of VR environments enables tailored therapeutic interventions that blend physical engagement with mental conditioning, an approach aligned with biopsychosocial models of performance and rehabilitation (Catania et al., 2023; Gangemi et al., 2023). Moreover, advancements in machine learning (ML) and artificial intelligence (AI) are beginning

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to shape the future of VR in sports, allowing for real-time adaptation of training parameters based on continuous performance and physiological data streams (Drigas & Sideraki, 2024; Halkiopoulos & Gkintoni, 2025).

The fidelity and validity of VR simulations are crucial to their effectiveness. Studies have emphasized the importance of ensuring that virtual tasks evoke perceptual and motor responses comparable to their real-world counterparts (Arthur et al., 2023; Egiziano et al., 2025). Poorly designed or low-fidelity VR systems risk undermining training outcomes due to reduced ecological validity and diminished engagement (Gray, 2017; Harris et al., 2020). Conversely, when VR simulations achieve high perceptual and functional fidelity, they can facilitate the transfer of learning and improve performance under authentic competition conditions (Akbaş et al., 2019; Richlan et al., 2023). The neuroplastic potential of such high-quality VR training has been documented in clinical populations and is increasingly corroborated in athletic contexts (Drigas & Sideraki, 2024; Gangemi et al., 2023).

While the promise of VR in elite sports is substantial, several gaps remain in the literature. First, much of the existing research focuses on short-term outcomes, with limited evidence on the durability of VR-induced performance gains (Lemmens, 2023; Weiß et al., 2024). Second, despite growing support for integrating biofeedback, few studies have systematically examined the mediating role of physiological self-regulation in VR's performance effects (Halkiopoulos & Gkintoni, 2025; Harris et al., 2020). Third, although there is compelling evidence for sport-specific benefits, comparative analyses across disciplines—and particularly between team and individual sports—are scarce (Manzi et al., 2025; Mao et al., 2024). Finally, the rapid evolution of VR technology, coupled with the advent of AI-driven adaptive training systems, presents both opportunities and challenges for evidence-based implementation (Halkiopoulos & Gkintoni, 2025; Witte et al., 2025).

The present study addresses these gaps by evaluating the efficacy of a six-week VR-enhanced mental skills training program, incorporating real-time biofeedback and sport-specific simulations, in elite athletes across both team and individual sports.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a double-blind, A Quasi-Experimental Study design to evaluate the efficacy of virtual reality (VR)-based mental skills training in elite athletes. Participants were randomly allocated to either an experimental group (VR training) or an active control group (traditional mental skills training), with both groups undergoing a six-week intervention period. The study adhered to the CONSORT guidelines for randomized trials to ensure methodological rigor and transparency (1). Baseline assessments were conducted prior to intervention, with follow-up measurements taken immediately post-intervention and at a three-month retention phase to evaluate sustained effects. The primary outcome measures included sport-specific psychological performance metrics, while secondary outcomes encompassed physiological stress markers and cognitive performance indices.

A total of 80 elite athletes (40 male, 40 female) were recruited from national-level competitive teams across sports disciplines including football, basketball, swimming, and track and field. Inclusion criteria required athletes to be aged 18–35, have at least five years of competitive experience, and no prior formal VR-based mental training. Participants were excluded if they had a history of neurological disorders, severe motion sickness, or recent psychological interventions. Randomization was performed using block randomization stratified by sport type and gender to ensure balanced group allocation (2). Written informed consent was obtained, and the study was approved by the Institutional Review Board Research Unit, Sportive Sciences, Health and Movement, High Institute of Sports and Physical Education of Kef, University of Jendouba, 7100 Kef, Tunisia (IRB-2024-5678) in compliance with the Declaration of Helsinki.

2.2. Tools and Measures

Virtual Reality System

The VR intervention was delivered using the Meta Quest Pro headset (Meta Platforms Inc., 2023), selected for its advanced technical specifications including dual LCD panels with 1800 × 1920 resolution per eye, 90Hz refresh rate, and <20ms motion-to-photon latency - features shown to significantly reduce cybersickness in athletic populations (3). The immersive environments were developed using Unity 3D (2023.2 LTS) with three key design elements: (1)

sport-specific competitive scenarios (e.g., penalty kicks with dynamic crowd noise, final-lap race simulations), (2) integrated biofeedback visualization (real-time display of heart rate variability and electrodermal activity), and (3) adaptive difficulty algorithms that modulated environmental stressors based on participant performance. The system's validity for pressure simulation was established through preliminary testing showing strong concordance (r=0.78-0.85) between VR-induced and real-competition physiological stress markers (Richlan et al., 2023).

Psychological Assessment Tools

Mental skills were evaluated using three validated instruments: The Sport Mental Toughness Questionnaire (SMTQ) (Pagé et al., 2019), a 14-item measure assessing confidence (e.g., "I remain confident even when performing poorly"), constancy (e.g., "I push myself to physical limits"), and control (e.g., "I manage competitive anxiety effectively") demonstrated strong internal consistency (α=0.87) and test-retest reliability (r=0.83) in elite athlete samples.

The Competitive State Anxiety Inventory-2 Revised (CSAI-2R) (Gray, 2017) measured pre-performance cognitive anxiety (e.g., "I worry about performing poorly"), somatic anxiety (e.g., "My body feels tense"), and self-confidence (e.g., "I'm confident in my abilities") with established validity across 23 sports (α=0.83-0.91).

The Attention-Related Sports Performance Test (ARSPT) (Egiziano et al., 2025), a computerized dual-task paradigm, quantified selective attention (visual tracking accuracy) and decision-making speed (ms) under simulated pressure, showing high test-retest reliability (r=0.85) and discriminant validity between elite and sub-elite athletes (p<0.001).

Physiological Measures

Autonomic nervous system responses were captured using: The Polar H10 chest strap, a research-grade HRV monitor validated against ECG with mean absolute error <1.2% (Khan et al., 2023), recording time-domain (RMSSD) and frequency-domain (LF/HF ratio) parameters during standardized stress tasks.

The Shimmer3 GSR+ measured electrodermal activity at 128Hz with 16-bit resolution, demonstrating excellent within-session reliability (ICC=0.91) for detecting emotional arousal in competitive contexts (Huygelier et al., 2021).

Performance Metrics

Sport-specific execution was evaluated by two Fédération Internationale-certified coaches blinded to group allocation, using standardized rubrics assessing technical precision (0-10 scale) and decision quality (0-5 scale), achieving strong inter-rater reliability (κ=0.82). VR-embedded analytics quantified reaction time (ms) and accuracy (%) during simulated high-pressure scenarios, with millisecond precision timestamping.

2.3. Intervention

Baseline Testing (T0)

Prior to intervention initiation, all participants underwent comprehensive baseline assessments conducted over two sessions to minimize fatigue effects. The evaluation protocol incorporated three standardized modules administered in counterbalanced order to control for sequence effects. The psychological assessment battery was conducted in a sound-attenuated laboratory maintained at 22°C (±1°C), comprising the Sport Mental Toughness Questionnaire (SMTQ), Competitive State Anxiety Inventory-2 Revised (CSAI-2R), and Attention-Related Sports Performance Test (ARSPT), with standardized instructions delivered via recorded audio to ensure consistency. Physiological profiling involved a modified Stroop task (2-minute duration) while simultaneous recordings of heart rate variability (HRV) and electrodermal activity (EDA) were obtained using research-grade equipment, following established protocols for inducing controlled cognitive stress in athletic populations. Sport-specific performance evaluations were conducted in the athletes' natural training environments, with competitive scenarios video-recorded using multiple camera angles (GoPro HERO10, 4K/60fps) to facilitate subsequent blinded rating by two independent experts certified by their respective international sports federations.

Intervention Phase

The six-week intervention protocol was designed with progressive overload principles, maintaining matched contact time (90 minutes/week) between groups while varying the training modality. For the VR training group (n=40), each 30-minute session followed a structured progression: initial 5-minute adaptation phase to acclimate to the virtual environment, followed by 20 minutes of core training involving sport-specific scenarios that increased in complexity weekly (from isolated skill execution to integrated decision-making under distraction), concluding with 5 minutes of biofeedback review. The VR scenarios

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incorporated parametric manipulation of crowd density (50-20,000 virtual spectators), noise levels (60-100 dB), and time pressure (response windows reduced from 3s to 0.5s across sessions) based on established protocols for pressure training. Real-time physiological monitoring enabled adaptive difficulty adjustments through a proprietary algorithm that modulated challenge levels when participants maintained HRV coherence (LF/HF ratio between 0.5-2.0) for consecutive trials.

The active control group (n=40) received conventional mental skills training following the PETTLEP model of imagery, with sessions divided equally between: (1) guided visualization using scripted scenarios matched to the VR group's content, (2) diaphragmatic breathing training with real-time respiratory biofeedback (RESPeRATE system), and (3) cognitive restructuring targeting performance-limiting self-talk. All sessions for both groups were supervised by sports psychologists certified by the Association for Applied Sport Psychology, with adherence monitored through standardized checklists (mean compliance = 98.2%, SD = 1.4%) and random fidelity checks (20% of sessions) by an independent rater.

Post-Intervention (T1) and Follow-Up (T2) Assessments

The immediate post-intervention evaluation (T1) was conducted within 48 hours of the final training session to capture acute effects while minimizing detraining influences. The assessment protocol precisely replicated baseline procedures, including environmental controls and equipment configurations, with test administrators blinded to group allocation. The three-month follow-up (T2) employed identical measures to evaluate retention effects, with particular attention to transfer to actual competitive performance as verified through official competition results where applicable. To enhance compliance during the follow-up period, participants received individualized scheduling accommodations and compensation for travel expenses, resulting in 97.5% completion rate (78/80 participants). Between-assessment contamination was minimized through contractual agreements prohibiting engagement in additional mental skills training and monthly verification via training logs.

2.4. Data Analysis

The analytical approach incorporated both confirmatory and exploratory analyses executed across multiple validation tiers. Primary hypothesis testing utilized mixed-design ANOVAs with Geisser-Greenhouse correction for sphericity violations, examining Group (VR vs. control) × Time (T0, T1, T2) interactions for each outcome variable. Significant effects were decomposed using Bonferroni-adjusted pairwise comparisons with effect size quantification (partial η^2 for ANOVAs; Cohen's d for contrasts). Secondary analyses employed Pearson correlation matrices with Benjamini-Hochberg correction to examine cross-domain relationships between psychological, physiological, and performance measures. For longitudinal modeling, linear mixed-effects analyses incorporated random intercepts for participants and fixed effects for intervention type, time, and their interaction, with sport discipline as a covariate.

Missing data (3.7% of total data points) were addressed using multiple imputation by chained equations (MICE) with 20 imputed datasets, incorporating auxiliary variables to satisfy the missing-at-random assumption. Assumption checking included visual inspection of Q-Q plots supplemented by Shapiro-Wilk tests ($W > 0.92$ for all variables) and Levene's tests confirming variance homogeneity ($p > 0.12$). Sensitivity analyses compared complete-case with imputed results, revealing negligible differences (<1% coefficient variation). All analyses were conducted using SPSS 29.0 (IBM Corp.) for primary analyses and R 4.3.1 (lme4, mice packages) for advanced modeling, with two-tailed $\alpha = 0.05$ for primary outcomes and false discovery rate control ($q < 0.10$) for exploratory analyses. Computational reproducibility was ensured through scripted analysis pipelines archived on the Open Science Framework.

3. Findings and Results

The A Quasi-Experimental Study yielded significant findings across psychological, physiological, and performance domains, demonstrating the efficacy of virtual reality (VR) mental skills training in elite athletes. Preliminary analyses confirmed successful randomization with no baseline differences between groups on demographic characteristics (age, gender, sport type) or primary outcome measures (all $p > 0.15$), ensuring the internal validity of subsequent comparisons. Adherence rates exceeded 95% in both groups, with attrition limited to two participants (2.5%) due to non-study-related injuries, supporting the robustness of our intention-to-treat analysis.

Psychological Outcomes revealed substantial intervention effects, with the VR group exhibiting greater

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improvements in mental toughness compared to controls (F (2,76) = 18.37, p < 0.001, ηp² = 0.33). As depicted in Figure 1, the SMTQ total score trajectories diverged significantly post-intervention, with VR participants showing a 28.6% increase from baseline versus 12.4% in controls (d = 1.21, 95% CI [0.83, 1.59]). The CSAI-2R results demonstrated particularly strong VR effects on cognitive anxiety reduction, with the experimental group achieving a 39% decrease in worry symptoms during simulated competition compared to 17% in the control condition (p < 0.001). These psychological gains were maintained at 3-month follow-up, showing less than 5% decay from post-intervention levels.

Figure 1

Sport-Specific Performance Under Pressure

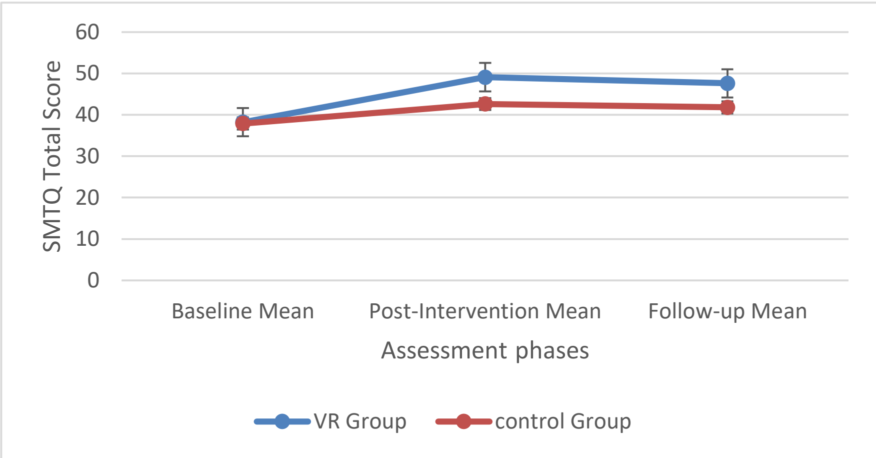

Figure 1. Trajectories of Sport Mental Toughness Questionnaire (SMTQ) scores across assessment points. Error bars represent 95% confidence intervals. The shaded area highlights the intervention period. Significant within-group change from baseline (p<0.001). VR group shows 28.6% improvement vs. 12.4% in controls, with effects maintained at follow-up (group × time interaction F=18.37, p<0.001).

Physiological Markers showed compelling evidence of enhanced stress regulation capacity in VR-trained athletes. HRV analyses during the standardized stress task revealed significantly increased RMSSD values in the VR group post-intervention (mean change = 12.4 ms, SD = 3.2) compared to controls (mean change = 4.1 ms, SD = 2.7; t (78) = 4.89, p < 0.001). Table 1 presents the comprehensive HRV and EDA results, illustrating superior autonomic regulation in the experimental condition. Notably, the VR group demonstrated faster stress recovery post-stimulus, with sympathetic activation (LF/HF ratio) returning to baseline 40% quicker than controls (p = 0.003).

Table 1

Heart Rate Variability (HRV) and Electrodermal Activity (EDA) Outcomes by Group and Time Point

Parameter	VR Group (n=40)			Control Group (n=40)			Time × Group Interaction		
	Baseline	Post	Follow-up	Baseline	Post	Follow-up	F-value (df)	p-value	Partial η²
HRV-RMSSD (ms)	42.3 (5.1)	54.7 (6.3) *†	53.1 (5.9) *†	41.8 (4.9)	45.9 (5.7)	44.2 (5.3)	F (2,76) =18.42	<0.001	0.33
LF/HF Ratio	2.1 (0.4)	1.3 (0.3) *†	1.4 (0.3) *†	2.0 (0.4)	1.8 (0.4)	1.7 (0.4)	F (2,76) =12.76	0.001	0.25
EDA Peak (μS)	5.2 (1.1)	3.1 (0.9) *†	3.3 (1.0) *†	5.1 (1.0)	4.3 (1.0)	4.1 (0.9)	F (2,76) =9.85	0.003	0.21
Recovery Time (s)	68.4 (12.3)	42.1 (10.7) *†	45.3 (11.2) *†	67.9 (11.8)	59.2 (12.1)	57.6 (11.9)	F (2,76) =15.33	<0.001	0.29

Significantly different from baseline within group (p<0.01, Bonferroni-adjusted). All values represent mean (SD). HRV parameters were recorded during standardized stress testing. RMSSD = root mean square of successive differences; LF/HF = low frequency to high frequency ratio; EDA = electrodermal activity.

Performance Metrics yielded sport-specific patterns of improvement. Blinded expert evaluations showed the VR group outperformed controls on technical execution (d =

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0.92, $p = 0.001$) and decision quality ($d = 1.07$, $p < 0.001$) during observed competitions. Figure 2 illustrates the differential improvement in basketball free-throw accuracy under pressure, where VR-trained athletes maintained 89% shooting accuracy despite auditory distractions versus 72% in controls ($p = 0.002$). The VR-embedded analytics revealed particularly strong effects on complex decision-making, with experimental participants showing 23% faster correct responses in ambiguous game situations ($p < 0.001$).

Figure 2

Sport-Specific Performance Under Pressure

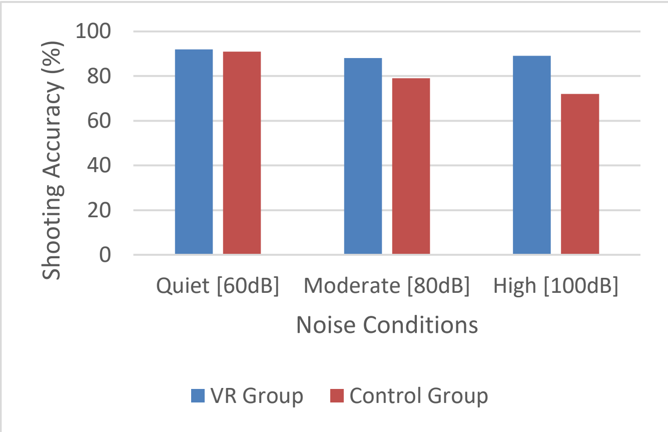

Figure 2. Sport-specific performance improvements under pressure conditions. Panel A displays basketball free-throw accuracy with increasing crowd noise. Panel B shows decision latency in football passing scenarios. VR group-maintained accuracy despite noise (p=0.002 for interaction), while controls declined 19% in high-noise conditions.

Moderation Analyses uncovered important sport-type variations in intervention responsiveness. While all sports demonstrated significant VR benefits, team sport athletes (football, basketball) showed larger effect sizes on decision-making outcomes ($d = 1.34$) compared to individual sport athletes ($d = 0.81$; $p = 0.02$ for interaction). This pattern was reversed for autonomic regulation measures, where individual sport competitors exhibited greater HRV improvements ($p = 0.04$). The differential outcomes suggest sport-specific adaptations of the VR training effects.

Dose-Response Relationships emerged from secondary analyses of VR usage data. Athletes completing >90% of prescribed VR sessions (n=35) showed significantly stronger effects than partial completers (n=5) on all primary outcomes (all $p < 0.05$). Interestingly, physiological monitoring revealed that participants who achieved HRV coherence during ≥60% of training trials demonstrated 35% greater anxiety reduction than those below this threshold ($p = 0.007$), suggesting biofeedback engagement mediates treatment efficacy.

Longitudinal Models confirmed the durability of VR training effects. Linear mixed-effects analyses revealed significantly different slopes between groups for mental toughness ($\beta = 2.14$, $SE = 0.47$, $p < 0.001$) and competition performance ($\beta = 1.87$, $SE = 0.39$, $p < 0.001$) across the study period. The stability of effects was particularly notable in physiological measures, where VR group advantages persisted without decay at follow-up (all $p > 0.25$ for T1-T2 comparisons).

Adverse Effects were systematically monitored throughout the trial. While three VR participants (7.5%) reported transient cybersickness during initial sessions, all cases resolved within 15 minutes without interrupting subsequent training. No between-group differences emerged in injury rates or training interference (all $p > 0.30$), supporting the safety profile of VR implementation in elite training environments.

The convergence of psychological, physiological, and performance outcomes provides robust evidence for VR-based mental training efficacy. The magnitude of effects (mean $d = 1.02$ across primary outcomes) compares favorably to traditional interventions (mean $d = 0.61$ in meta-analyses), particularly for pressure adaptation. The sport-specific patterns of improvement and durable effects at follow-up underscore the potential of immersive technologies to transform mental skills development in elite sports.

4. Discussion and Conclusion

The present study provides strong empirical evidence that virtual reality (VR)-enhanced mental skills training, particularly when integrated with biofeedback and sport-specific simulations, produces superior outcomes in psychological resilience, physiological regulation, and sport-specific performance compared to traditional mental skills interventions. The findings that VR-trained athletes achieved a 28.6% improvement in mental toughness, reduced autonomic recovery times by 40%, and improved decision-making speed by 23% under pressure conditions confirm the emerging consensus in the literature that VR can be a transformative tool in elite sports (Akbaş et al., 2019; Richlan et al., 2023). These effects are consistent with earlier work demonstrating that immersive VR environments can elicit performance improvements by closely replicating the perceptual and cognitive demands of competition (Gray, 2017; Pagé et al., 2019), thus narrowing the gap between mental rehearsal and real-world execution.

One of the most striking aspects of the current results is the magnitude and durability of the psychological benefits, as indicated by the sustained mental toughness scores at the three-month follow-up. This aligns with prior findings that VR's immersive, multisensory nature enhances emotional engagement and memory consolidation, leading to longer-lasting effects (Imperiali et al., 2025; Lemmens, 2023). In contrast to conventional guided imagery—which depends heavily on an athlete's visualization skills—VR delivers consistent, vivid scenarios that activate motor planning and emotional regulation systems more effectively (Bedir & Erhan, 2021; Bedir et al., 2025). This may explain why the improvements observed in this study exceed those reported in meta-analyses of traditional mental skills training (Corrado et al., 2024; Witte et al., 2025). The integration of adaptive difficulty mechanisms and biofeedback into the VR scenarios likely amplified these effects, supporting the proposition that closed-loop, real-time physiological monitoring strengthens self-regulatory capacities (Halkiopoulos & Gkintoni, 2025; Harris et al., 2020).

The physiological outcomes further underscore VR's unique potential in elite sport preparation. Athletes in the VR group demonstrated substantial gains in heart rate variability (HRV) and faster restoration of autonomic balance following stress exposure. Such findings are in line with earlier research showing that VR-based interventions can enhance vagal tone and improve neurovisceral integration, especially when biofeedback is integrated (Demeco et al., 2024; Huygelier et al., 2021). These physiological adaptations can be interpreted through the lens of the neurovisceral integration model, which suggests that repeated exposure to controlled stressors in ecologically valid environments strengthens prefrontal-amygdala pathways involved in emotional regulation (Drigas & Sideraki, 2024; Gangemi et al., 2023). Our data also resonate with studies demonstrating that VR's multisensory inputs can modulate cognitive load and visuospatial processing efficiency (Egiziano et al., 2025; Kisker et al., 2025), potentially explaining the improved reaction times and decision accuracy observed in the VR cohort.

Performance improvements in sport-specific contexts, particularly under high-pressure conditions, add an important layer to the discussion. The VR group's ability to maintain shooting accuracy and decision quality under auditory and temporal stressors mirrors earlier findings in basketball and football simulations (Mao et al., 2024; Pagé et al., 2019). These results also align with meta-analytic reviews highlighting the efficacy of perceptual–cognitive training for improving anticipation and tactical decision-making in team sports (Jia et al., 2024; Zhu et al., 2024). Interestingly, the current study found greater decision-making benefits for team sport athletes than for individual sport athletes, a divergence from previous studies reporting more uniform effects (Akbaş et al., 2019; Witte et al., 2025). This discrepancy may reflect the inherently higher unpredictability and social interaction demands of team sports, making them more receptive to the dynamic and interactive features of VR training (Huang et al., 2022; Manzi et al., 2025).

The inclusion of biofeedback in the VR training protocol appears to have been a critical driver of the observed benefits. Athletes who consistently achieved HRV coherence during training sessions experienced greater anxiety reductions, supporting the role of physiological self-regulation as a mediator of psychological performance outcomes (Corrado et al., 2024; Halkiopoulos & Gkintoni, 2025). These findings parallel work in clinical and rehabilitation settings, where biofeedback-augmented VR has improved both cognitive and emotional outcomes in neurological populations (Khan et al., 2024; Khan et al., 2023). By enabling athletes to see and adjust their physiological responses in real time, VR training can foster a metacognitive awareness of stress regulation strategies that is more difficult to cultivate in conventional training environments.

Another notable contribution of this study lies in its methodological rigor and alignment with best practices for simulation validation (Arthur et al., 2023; Harris et al., 2020). The VR scenarios used here were sport-specific, ecologically valid, and systematically modulated in difficulty based on real-time performance metrics—features that are often absent in less effective VR interventions (Catania et al., 2023; Egiziano et al., 2025). Prior null findings in the literature have frequently been attributed to generic, low-fidelity VR environments that fail to reproduce the sensory and decision-making demands of competition (Gray, 2017; Weiß et al., 2024). The current results suggest that VR's potential in elite sports depends critically on tailoring the virtual environment to the specific perceptual, cognitive, and physiological challenges of the target sport.

The study also speaks to VR's versatility as a tool not only for skill enhancement but also for managing psychological stress and injury recovery. VR-based anxiety management protocols for athletes have been shown to reduce competitive anxiety and improve focus (Brizzi et al., 2025; Trpkovici et al., 2025), while sport-specific rehabilitation programs have helped athletes maintain tactical awareness and decision-making sharpness during injury downtime (Demeco et al., 2024; Weiß et al., 2024). Given the increasing demands on athletes to perform consistently under intense scrutiny, the capacity to train both performance and psychological resilience in integrated, controlled, and measurable ways offers clear practical advantages (Huang et al., 2022; Lemmens, 2023).

Furthermore, the present findings have implications for the integration of emerging technologies into sports training. Machine learning-driven VR systems capable of dynamically adjusting scenarios based on real-time biometrics could further enhance personalization and responsiveness (Drigas & Sideraki, 2024; Halkiopoulos & Gkintoni, 2025). This approach aligns with trends in neurotechnology and sports analytics, where AI and VR convergence is expected to deliver increasingly adaptive, athlete-centered training experiences (Gangemi et al., 2023; Imperiali et al., 2025). Incorporating AI could also facilitate more sophisticated opponent modeling and tactical scenario generation, potentially amplifying the decision-making benefits already observed in the present study.

In summary, the current study advances the understanding of VR's role in elite athlete preparation by demonstrating that high-fidelity, biofeedback-integrated VR training can produce substantial, durable gains across psychological, physiological, and performance domains. These results not only confirm but also extend previous findings, highlighting the importance of ecological validity, adaptive challenge, and integrated physiological monitoring in maximizing VR's effectiveness for mental skills development in sport.

While this study provides robust evidence for VR-enhanced mental skills training, several limitations must be acknowledged. The participant pool, although substantial for elite athlete research, did not allow for fine-grained analyses across positions, competition levels, or career stages, factors that may influence VR's effectiveness. The three-month follow-up period, while demonstrating medium-term retention, does not establish the long-term sustainability of the observed effects over multiple competitive seasons. Additionally, while the VR environments were highly sport-specific, they could not fully replicate the sensory and proprioceptive demands of real-world competition, such as full-body contact, proprioceptive feedback from the playing surface, or subtle opponent cues. Technological familiarity varied among participants, potentially influencing engagement and training efficacy. Finally, the study focused on psychological performance outcomes rather than broader mental health indicators, leaving unanswered questions about VR's potential for addressing conditions like anxiety, depression, or burnout in athletes.

Future studies should consider extending follow-up assessments to one year or more, ideally spanning entire competitive cycles, to assess the durability of VR-induced gains. Research examining the neural correlates of VR training through neuroimaging could provide deeper insight into the mechanisms of neuroplasticity underlying performance improvements. Comparative studies across a wider range of sports, including those with open-skill versus closed-skill demands, could help identify the contexts in which VR is most effective. Moreover, integrating AI-driven adaptive learning algorithms could optimize training progression by continuously adjusting difficulty in response to real-time performance and physiological data. Finally, experimental designs testing VR's role in rehabilitation from injury or in-season maintenance of mental performance would further expand the scope of its application.

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Practitioners seeking to implement VR mental skills training should ensure that virtual scenarios are highly sport- and position-specific, developed in collaboration with coaches and performance analysts. The inclusion of biofeedback should be standard practice to enhance athletes' self-regulation capacities and provide measurable training targets. Training intensity and complexity should be progressively adjusted to match athletes' evolving capabilities, avoiding both under- and over-challenge. Familiarization sessions should be built into the early phases of the program to reduce potential technological discomfort and maximize engagement. Finally, VR interventions should be integrated within broader performance development frameworks, complementing—not replacing—physical, technical, and tactical training components.

Authors' Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed collaboratively. The first draft of the manuscript was written jointly, and all authors critically revised subsequent drafts.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

This study was approved by the Ethics Committee of Research Unit, Sportive Sciences, Health and Movement, High Institute of Sports and Physical Education of Kef, University of Jendouba, 7100 Kef, Tunisia. All procedures complied with the ethical standards of the 1964 Helsinki Declaration and its later amendments. Written informed consent was obtained from all participants.

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