Game Nexus

Factors Influencing Transfer of Motor Skills from Virtual Reality to On-Field Performance in Racket Sports

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ABSTRACT

This study aimed to explore the factors influencing the transfer of motor skills acquired in virtual reality (VR) environments to on-field performance in racket sports. A qualitative research design was employed using semi-structured interviews with 19 participants from the United States, including athletes, coaches, and performance specialists across tennis, badminton, and squash. Participants were recruited through purposive sampling, and interviews continued until theoretical saturation was reached. Each interview lasted between 45 and 75 minutes, was audio-recorded, and transcribed verbatim. NVivo 14 software was used to manage and code the data. An inductive thematic analysis was applied, moving through stages of open coding, axial coding, and selective coding to identify patterns and themes. Trustworthiness was ensured through peer debriefing, audit trails, and participant validation. Four overarching themes were identified: (1) Fidelity of VR training environments (including visual and spatial realism, haptic and sensory feedback, and customization of scenarios), (2) Athlete psychological and cognitive factors (such as motivation, confidence, attention, cognitive load, and transfer mindset), (3) Coaching and instructional integration (highlighting coach involvement, feedback mechanisms, program design, and institutional support), and (4) Transfer conditions to on-field performance (including physical adaptation, perceptual-motor coupling, contextual similarity, performance pressure, injury prevention, and long-term retention). Participants emphasized that ecological fidelity, motivational engagement, coaching structures, and contextual similarity were decisive in whether VR-acquired skills translated effectively to real competition. The findings demonstrate that VR can support motor skill acquisition and transfer in racket sports, but its effectiveness depends on the integration of technological fidelity, psychological readiness, instructional frameworks, and contextual similarity. VR should be regarded as a complementary tool rather than a replacement for traditional training, with potential to enhance anticipation, confidence, and safe repetition if applied strategically.

Keywords: Virtual reality; motor learning; skill transfer; racket sports; qualitative research; sport training; performance adaptation

Introduction

The phenomenon of motor learning transfer is fundamentally rooted in neural adaptation. Recent evidence demonstrates that aligning neural population patterns can enhance the likelihood of successful transfer between tasks, suggesting a strong neurobiological substrate for generalization processes (1). In clinical populations, repetitive practice has been shown to enhance motor adaptability even in cases of neurological impairments such as cerebellar ataxia (2). These insights indicate that skill transfer is not limited to elite athletes but is a universal aspect of human motor behavior, though its success is dependent on both internal and external constraints.

The role of perceptual-motor coupling is central to this process. Research in interceptive tasks highlights the importance of integrating perception and action for accurate skill execution (3). Notably, studies on context-specific learning reveal that it is the visual properties of action consequences—rather than the environment itself—that drive motor learning specificity (4). This suggests that VR training systems must carefully replicate outcome-related cues, such as the trajectory and timing of a ball in racket sports, if they are to foster effective transfer.

However, transfer is rarely symmetrical. Investigations into perceptual-motor learning reveal asymmetries in transfer patterns, indicating that learning from one modality or direction may not equivalently reverse into the opposite (5). This aligns with broader debates on similarity judgments and the limits of generalization. Complementary to this, evidence from music training demonstrates that complex cognitive-motor functions underlie skill transfer, particularly in older adults (6). These studies collectively underscore that transfer is shaped not only by task structure but also by the cognitive-motor demands placed upon the learner.

Age and memory factors also contribute significantly. Reactivation of memory traces has been shown to influence age-related differences in skill transfer, suggesting that younger and older populations may differ in their ability to retain and reapply motor skills (7). Beyond age, cognitive strategies play a central role in how transfer occurs. Research on task components illustrates that learners are capable of transferring abstract strategies across superficially different tasks if common structures are recognized (8). In sports training, this implies that athletes may benefit from VR drills that emphasize not only physical replication but also strategic and perceptual elements shared with real-world play.

Neuroscientific advances provide further nuance to these findings. A combinatorial neural coding system has been proposed to underlie long-term motor memory, enabling flexible retrieval of skills across contexts (9). Similarly, algorithmic models have been developed to explain visually guided interceptive actions, with harmonic ratios and stimulation invariants providing a mathematical framework for perception–action coupling (10). These models have been extended to VR and augmented reality applications, where enhancing motion perception through algorithmic implementation is seen as crucial for effective training transfer (11). Such theoretical models contribute to the design of VR systems capable of delivering ecologically valid training scenarios for racket sport athletes.

Motor learning is also subject to modulation by broader experiential and environmental factors. For example, characterizing practice-dependent motor learning in stroke survivors reveals how the nervous system adapts differentially depending on the amount and type of practice (12). Reviews of motor learning in golf confirm that domain-specific constraints, including task complexity and attentional demands, influence how skills are acquired and transferred (13). Furthermore, experimental research on bimanual sequence learning emphasizes the role of task integration, showing that the degree of integration determines whether learned skills generalize beyond the original context (14).

Cognitive frameworks add further depth to understanding transfer. Theories of internally guided motor skills demonstrate how cognitive representations interact with motor processes to shape learning (15). Similarly, statistical learning research indicates that prior motor actions can outweigh sensory cues, suggesting that learners rely heavily on their own action histories when adapting to new tasks (16). Functional neuroimaging studies of motor sequences differentiate between sequence learning and motor execution, highlighting that distinct neural circuits support different aspects of skill transfer (17). Collectively, these insights demonstrate the interplay between cognition, perception, and neural organization in shaping how motor skills learned in one context are re-applied in another.

The relevance of transfer extends beyond motor learning to educational domains. Research in second language education emphasizes that transfer involves both explicit teaching for generalization and learner belief in applicability (18). Analogously, VR sport training may be most effective when athletes not only acquire skills in VR but also explicitly reflect on how those skills connect to on-field performance. Studies on balance tasks further confirm the impact of prior practice, showing that earlier experiences modulate later training adaptations (19). However, investigations in football players found no consistent evidence of motor transfer across whole-body sensorimotor tasks, illustrating the task-dependence of transfer processes (20).

More recently, investigations into neural and cortical mechanisms have highlighted additional dimensions. Interlimb transfer of visuomotor tasks is linked to interhemispheric inhibition, demonstrating a neurophysiological basis for cross-limb generalization (21). Similarly, research into the pre-supplementary motor cortex shows that transfer from perceptual to motor timing is mediated by specific cortical structures (22). At the cognitive level, flexibility research reveals that task sets define the boundaries within which learned adaptations can transfer, imposing constraints on generalization (23). These findings together demonstrate that transfer operates at multiple levels—from cortical inhibition to high-level task representations.

The implications for VR-based sport training are profound. Advances in artificial intelligence and task-informed meta-learning suggest that adaptive systems can be built to optimize training by tailoring tasks to learners' needs (24). Yet, challenges remain. Research on visuomotor adaptation indicates that fast and slow learning processes generalize differently across tasks such as locomotion and pointing, underscoring the need to distinguish between short-term adaptation and long-term skill retention (25). Studies on savings in motor adaptation further demonstrate that previously acquired adaptations can accelerate re-learning, highlighting opportunities to use VR as a platform for reinforcing prior experiences (26). Moreover, computational models continue to advance, with vision-and-language approaches demonstrating cross-domain generalization in medical diagnosis tasks (27). These models provide a conceptual bridge for considering how cross-domain learning may apply in VR-to-field transfer.

At the same time, critical reflections point out limitations. For example, cultural and pedagogical considerations affect whether learners perceive VR-based training as relevant or transferable, echoing challenges faced in other domains such as music education (6). Similarly, motor learning transfer studies in golf and other sports emphasize that task specificity and ecological validity remain decisive factors (13).

Taken together, this body of research establishes a complex, multi-layered understanding of motor skill transfer. It encompasses neural coding, cognitive representations, perceptual-motor coupling, age-related differences, and the influence of environmental and instructional factors. For racket sports, where performance hinges on precise timing, anticipation, and adaptability, VR presents both opportunities and challenges as a training medium. While VR environments can replicate perceptual and strategic demands, questions remain about how effectively such training translates to real-world match conditions.

Therefore, the present study aims to explore the factors influencing the transfer of motor skills from VR training environments to on-field performance in racket sports, with particular attention to the perspectives of athletes, coaches, and performance specialists.

Methods and Materials

Study Design and Participants

This study employed a qualitative research design to explore the factors influencing the transfer of motor skills from virtual reality (VR) training environments to on-field performance in racket sports. A purposive sampling strategy was adopted to ensure the inclusion of participants with direct experience in both VR-based training and competitive racket sports. The final sample consisted of 19 participants from the United States, including athletes, coaches, and performance specialists across tennis, badminton, and squash. Recruitment continued until theoretical saturation was achieved, meaning no new themes or insights emerged from the data. This approach ensured both depth and breadth in capturing the lived experiences and professional perspectives relevant to the phenomenon under study.

Data Collection

Data were collected through semi-structured, in-depth interviews. An interview guide was developed to balance consistency and flexibility, allowing participants to elaborate on their unique experiences while ensuring all core topics were addressed. Questions centered on perceptions of motor skill acquisition in VR settings, perceived similarities and differences between VR and on-field contexts, and the challenges and facilitators of skill transfer. Each interview lasted between 45 and 75 minutes and was conducted either face-to-face or via secure online video conferencing platforms, depending on participant availability and preference. All interviews were audio-recorded with participant consent and transcribed verbatim for analysis.

Data analysis

Data analysis followed an inductive thematic approach, supported by NVivo 14 software to manage and organize the transcripts systematically. The analysis proceeded in multiple stages, beginning with open coding to identify initial concepts, followed by axial coding to group related codes into broader categories, and selective coding to refine and integrate the emerging themes. Constant comparison was employed throughout the process to ensure consistency and rigor, with the research team iteratively reviewing the data until consensus was reached on the final set of themes. To enhance trustworthiness, strategies such as peer debriefing, maintaining an audit trail, and participant validation were incorporated.

Findings and Results

A total of 19 participants took part in the study, consisting of athletes, coaches, and performance specialists in racket sports from the United States. Among them, 11 were athletes actively engaged in tennis, badminton, or squash (57.9%), six were coaches with at least five years of professional experience (31.6%), and two were performance specialists working in sport science support roles (10.5%). The participants included 12 males (63.2%) and 7 females (36.8%), with ages ranging from 21 to 48 years (M = 32.6). In terms of sporting background, 8 participants (42.1%) were from tennis, 6 (31.6%) from badminton, and 5 (26.3%) from squash. Most athletes reported competitive experience at the national level (9 participants, 47.4%), while others had regional (6 participants, 31.6%) or international-level exposure (4 participants, 21.0%).

Table 1. Thematic Structure of Factors Influencing Transfer of Motor Skills from VR to On-Field Performance in Racket Sports

Category (Main Theme)	Subcategory	Concepts (Open Codes)
1. Fidelity of VR Training Environment	Visual and spatial realism	Court dimensions accuracy, racket tracking precision, realistic opponent avatars, ball trajectory authenticity, lighting and shadow cues
	Haptic and sensory feedback	Racket vibration simulation, ball impact feel, tactile glove feedback, sensory immersion, response delay concerns
	Movement constraints	Limited mobility space, headset weight, controller grip differences, movement calibration errors
	Rule and scoring integration	Virtual umpire presence, scorekeeping accuracy, adherence to sport rules, real-time penalty cues
	Audio-visual synchronization	Sound of racket-ball contact, crowd noise simulation, audio delay issues, immersive background sounds
	Customization of scenarios	Adjustable difficulty, training drills replication, opponent behavior programming, environmental variability
2. Athlete Psychological and Cognitive Factors	Motivation and engagement	Novelty appeal, game-like enjoyment, competitive drive, VR boredom reduction, increased training adherence

	Confidence building	Safe practice environment, overcoming fear of mistakes, gradual skill progression, psychological readiness
	Attention and focus	Reduced external distractions, focus on opponent cues, concentration enhancement, task engagement
	Cognitive load	Information overload, multitasking difficulty, memory retention, decision-making under pressure
	Transfer mindset	Belief in VR usefulness, openness to new methods, resistance to change, expectation alignment
3. Coaching and Instructional Integration	Coach involvement	Guidance during VR sessions, feedback interpretation, tailored instructions, encouragement
	Feedback mechanisms	Real-time performance metrics, video replay analysis, biomechanical corrections, personalized cues
	Training program design	Session frequency, balance between VR and on-field practice, progression planning, periodization
	Athlete–coach communication	Discussion of VR results, collaborative goal-setting, feedback acceptance, clarity in instructions
	Pedagogical adaptation	Adjusting drills to VR capabilities, aligning with skill development stages, creativity in drill design
	Institutional support	Club investment in VR, resource allocation, organizational encouragement, policy endorsement
	Peer influence	Team acceptance of VR, peer motivation, shared experiences, group training synergy
4. Transfer Conditions to On-Field Performance	Physical adaptation	Racket weight adjustment, footwork translation, body positioning, balance control
	Perceptual-motor coupling	Eye–hand coordination transfer, anticipation skills, depth perception, timing accuracy
	Contextual similarity	Match environment resemblance, opponent variability, court surface familiarity, environmental stressors
	Performance pressure	Managing competitive anxiety, replicating stress scenarios, coping with crowd presence, time constraints
	Injury prevention and risk	Reduced overuse injuries, safe repetitive practice, injury misalignment concerns
	Long-term retention	Skill consolidation, memory encoding, sustainable transfer, practice frequency effects

Fidelity of VR Training Environment

Visual and spatial realism. Participants highlighted the importance of accurate visual and spatial representation in VR environments. Several noted that when “the court lines are slightly off or the ball bounce doesn’t look right, it throws me off when I get back on the real court” (Participant 7). Accurate replication of court dimensions, realistic opponent avatars, and natural ball trajectories were described as essential for ensuring a seamless transfer of skills.

Haptic and sensory feedback. Many athletes pointed out that limited tactile feedback reduced the authenticity of training. As one coach observed, “The lack of real ball impact makes it harder for players to feel timing and adjust their strokes” (Participant 12). Features such as racket vibration and sensory immersion were seen as partially effective but still insufficient compared to on-field play.

Movement constraints. Several interviewees described movement limitations due to equipment design. One athlete shared, “I can’t lunge or dive properly because the headset feels heavy and the space is small” (Participant 3). Such restrictions made certain footwork patterns difficult to replicate, highlighting a gap between VR and real-world execution.

Rule and scoring integration. The incorporation of scoring and officiating features was perceived positively. Athletes appreciated the presence of “a virtual umpire keeping the score, which makes it feel like a real match” (Participant 9). This helped maintain focus and fostered a sense of competitive authenticity.

Audio-visual synchronization. Participants emphasized the significance of synchronized sound effects, particularly the sound of racket-ball contact. A coach explained, “When the audio doesn’t match the hit, it breaks the rhythm” (Participant 14). Realistic crowd noise and background sounds were also valued for simulating match conditions.

Customization of scenarios. Athletes favored the ability to adjust difficulty levels and opponent behavior. As one participant stated, “I liked being able to set the opponent to be more aggressive, which prepared me for real competition” (Participant 5). Such customizable features enhanced both engagement and skill transfer.

Athlete Psychological and Cognitive Factors

Motivation and engagement. Interviewees expressed that VR training fostered excitement and enjoyment, which increased adherence. A young athlete remarked, “It feels more like a game than practice, so I keep wanting to do it” (Participant 16). The gamified nature of VR was seen as a driver for sustained training motivation.

Confidence building. Participants described VR as a safe environment to experiment and overcome fears. One athlete noted, “I could practice my backhand without worrying about messing up in front of others” (Participant 11). This supportive setting enhanced self-assurance and encouraged risk-taking in skill practice.

Attention and focus. Several respondents explained that VR reduced distractions and sharpened their focus. “When I’m in the headset, all I see is the opponent and the ball, nothing else,” (Participant 8) shared an athlete, suggesting VR fosters attentional control critical for performance.

Cognitive load. Some participants identified challenges with information overload. A coach reported, “The players sometimes struggle with too many metrics flashing on the screen, and it distracts them” (Participant 2). Balancing useful feedback with cognitive simplicity was emphasized as a key design need.

Transfer mindset. Belief in VR’s effectiveness influenced actual skill transfer. Athletes who trusted the process were more likely to apply skills on the field. As one participant explained, “If you don’t believe it works, you won’t try those skills in a real match” (Participant 17).

Coaching and Instructional Integration

Coach involvement. Participants noted that coaching presence was crucial during VR training. One coach commented, “If I guide them while they play in VR, they make connections faster to real-life drills” (Participant 10). Guidance helped bridge the gap between VR sessions and on-field practice.

Feedback mechanisms. Athletes valued immediate feedback features, such as replay analysis and biomechanical cues. “Seeing the replay of my swing right after hitting in VR made me correct things much faster” (Participant 6), explained one player. Personalized cues were considered essential for effective learning.

Training program design. Respondents emphasized the need for structured integration of VR and traditional training. A participant stated, “We can’t just replace court time with VR, it has to complement it” (Participant 4). Balancing frequency and progression was highlighted as critical for long-term benefits.

Athlete–coach communication. Interviewees stressed that discussing VR performance results with coaches enhanced skill transfer. As one player shared, “When I talked to my coach about what I saw in VR, it made sense how it fit into my real matches” (Participant 13).

Pedagogical adaptation. Coaches described the importance of adapting teaching strategies to VR. “I redesigned drills so they matched what VR can do—otherwise it’s a wasted opportunity” (Participant 18), noted one coach. Aligning VR sessions with athlete development stages improved learning relevance.

Institutional support. Participants highlighted that organizational investment in VR influenced its usage. "If the club doesn't back it with resources, athletes won't take it seriously" (Participant 1). Institutional encouragement was seen as a signal of legitimacy.

Peer influence. Team culture shaped attitudes toward VR. An athlete observed, "When my teammates were excited about VR, I wanted to use it more too" (Participant 15). Shared experiences reinforced motivation and normalized VR adoption.

Transfer Conditions to On-Field Performance

Physical adaptation. Participants discussed challenges in adapting VR-trained movements to physical contexts. "The VR racket feels lighter, so adjusting to my real racket takes time" (Participant 19) explained one athlete. Footwork translation and body balance were also identified as transfer barriers.

Perceptual-motor coupling. Eye–hand coordination and anticipation skills were frequently cited as transferable benefits. A participant described, "VR really trained me to anticipate ball direction better" (Participant 9). Timing accuracy was also emphasized as a critical advantage.

Contextual similarity. The closer VR environments resembled actual match conditions, the greater the transfer. One coach shared, "When the court in VR looked like our tournament venue, players felt more prepared" (Participant 7). Familiarity with surfaces and stressors increased confidence.

Performance pressure. VR simulations that replicated stress scenarios were considered valuable. "Practicing with virtual crowds yelling at me helped me deal with nerves in real games" (Participant 2). Such features helped athletes manage competitive anxiety.

Injury prevention and risk. Several athletes noted VR's role in reducing injury risk by enabling repetitive practice without physical strain. "I could repeat strokes for an hour without worrying about my shoulder" (Participant 5). However, misalignment concerns were mentioned by some participants.

Long-term retention. Participants indicated that repeated VR practice supported memory consolidation. "After training in VR all week, I remembered the same patterns on the court" (Participant 14). Regular reinforcement was seen as necessary for sustainable transfer.

Discussion and Conclusion

The purpose of this study was to explore the factors influencing the transfer of motor skills from virtual reality (VR) training environments to on-field performance in racket sports, as perceived by athletes, coaches, and performance specialists. Through semi-structured interviews with 19 participants, four overarching themes emerged: fidelity of VR training environments, athlete psychological and cognitive factors, coaching and instructional integration, and transfer conditions to on-field performance. These themes highlight the interplay between technological fidelity, cognitive-motivational dynamics, instructional frameworks, and contextual factors in shaping transfer outcomes.

Participants emphasized that the ecological validity of VR environments played a central role in whether skills acquired could translate effectively to real matches. Specifically, visual and spatial realism, haptic and sensory feedback, and audio-visual synchronization were repeatedly cited as either enablers or barriers to transfer. These findings resonate with the proposition that the alignment of neural population patterns is crucial for motor learning transfer, as even subtle discrepancies between VR and real-world cues can disrupt this process (1). The reported importance of ball trajectory accuracy and opponent avatars aligns with research showing that perception–action coupling is fundamental for discriminative interceptive actions (3).

The lack of authentic haptic cues was described by several athletes as a major obstacle to skill generalization. This aligns with studies on context-specific motor learning, which demonstrate that it is the sensory properties of action consequences, not environmental context alone, that drive specificity (4). Thus, VR tools that fail to reproduce the tactile "feel" of a racket-ball impact may limit the degree of transfer. Similarly, the role of customization in VR scenarios reported by participants mirrors findings from golf training, where task-specific variability and adaptability are essential for meaningful learning (13).

Another subtheme—rule and scoring integration—suggests that competitive authenticity supports transfer. Athletes described that the presence of a "virtual umpire" enhanced motivation and created a game-like environment. Comparable effects have been noted in educational contexts, where the explicit teaching for transfer enhances the likelihood that learners apply knowledge beyond its original context (18). Together, these results highlight the need for VR environments to replicate not only the physical but also the structural and motivational characteristics of sport competition.

Motivation and engagement emerged as key facilitators of VR-based skill transfer. Participants explained that VR felt more like a game, which reduced boredom and encouraged consistent practice. This echoes research showing that repetitive practice promotes adaptability even in populations with neurological impairments such as cerebellar ataxia (2). The gamified nature of VR thus appears to provide the repetitive exposure necessary for neural consolidation, while simultaneously maintaining athlete motivation.

Confidence-building was another important finding. Athletes noted that VR provided a safe environment to experiment with techniques without the fear of failure. This aligns with studies demonstrating that prior practice influences later training adaptations, such as in balance learning (19), and with evidence that previous motor actions can outweigh sensory information in statistical learning (16). VR's ability to create a psychologically safe training space may therefore allow athletes to accumulate motor experiences that later shape their responses under pressure.

Attention and focus were also emphasized, with participants describing how VR reduced distractions. This aligns with neuroscientific findings on motor sequence learning, which suggest that distinct neural circuits underlie the integration of perceptual focus and motor execution (17). Conversely, some athletes described experiencing cognitive overload due to excessive performance metrics in VR. This observation finds support in research on task sets and cognitive flexibility, which emphasizes that task demands define the boundaries of successful adaptation (23). VR designers must therefore balance informative feedback with cognitive simplicity to maximize attentional benefits.

Finally, the "transfer mindset" reported by participants—that belief in VR's usefulness influenced real-world application—aligns with research in language transfer showing that learners' expectations and beliefs shape transfer efficacy (18). In the context of sport, psychological openness to VR training appears to act as a mediating factor in whether athletes actually attempt to apply learned skills on the field.

The third theme emphasized the role of coaches and instructional design in shaping VR-to-field transfer. Coach involvement, feedback mechanisms, and program design were consistently mentioned by participants. This finding resonates with evidence that whole-body skill transfer in football was not consistently observed without structured training integration (20). It suggests that VR training in isolation is insufficient; rather, it must be embedded within a broader pedagogical framework.

Athletes valued immediate feedback such as video replay and biomechanical corrections, which mirrors studies on interlimb transfer and cortical inhibition showing that specific feedback can facilitate cross-limb and interhemispheric generalization (21). Moreover, the importance of athlete–coach communication echoes broader evidence that task integration determines whether learning generalizes beyond the original setting (14). Coaches serve as mediators who translate VR experiences into on-field adjustments, reinforcing the bridge between environments.

Institutional support and peer influence were also highlighted. Athletes reported that club investment legitimized VR use, while peer enthusiasm shaped motivation. These social dimensions reflect insights from studies in music learning, where broader cognitive-motor contexts—including cultural and motivational elements—shape transfer outcomes (6). Likewise, transfer asymmetry findings (5) suggest that instructional structures are necessary to mitigate uneven transfer effects. Thus, social and institutional ecosystems are as critical as technological fidelity in ensuring VR's effectiveness.

The final theme focused on the conditions necessary for effective transfer. Athletes described challenges in adapting VR-practiced movements to physical environments, such as racket weight differences and limited space for footwork. This observation resonates with findings that visuomotor adaptation generalizes differently across locomotion and pointing tasks (25). Physical adaptation therefore appears to be a limiting factor in VR-to-field transfer, with task-specific differences influencing generalization.

Perceptual-motor coupling was one of the most frequently cited benefits. Athletes explained that VR improved their anticipation and timing, which aligns with models of visually guided interceptive actions based on harmonic ratios and invariants (10). These findings also connect with algorithmic approaches that enhance motion perception in VR and AR systems (11), suggesting that perceptual training components may transfer more readily than gross motor adaptations.

Contextual similarity was described as a critical determinant. Athletes felt more prepared when VR environments resembled real courts, which reflects evidence that similarity judgments drive transfer asymmetry (5). Moreover, the reported effectiveness of VR in replicating competitive stress echoes findings on memory reactivation and age differences, which demonstrate that contextual cues influence retention and transfer (7). VR scenarios that simulate stressors such as crowds or time pressure may therefore build resilience for real-world competition.

Injury prevention was another reported benefit, as VR allowed for repetitive practice without overuse risks. This aligns with evidence that prior motor actions and adaptations can create savings, reducing the physical toll of repeated learning (26). Finally, long-term retention described by athletes—where VR-trained patterns resurfaced in real matches—connects with theories of combinatorial neural coding for long-term motor memory (9). This suggests that VR practice can contribute to durable skill consolidation if reinforced through consistent training.

Taken together, the findings of this study illustrate that VR-to-field motor skill transfer in racket sports is a multifactorial process influenced by technological, psychological, instructional, and contextual factors. The emphasis participants placed on fidelity echoes a broad body of evidence demonstrating the importance of sensory and perceptual accuracy for transfer (3, 4). At the same time, psychological and motivational findings underscore the parallels between sport and educational domains, where learner belief and engagement strongly mediate transfer (18).

The importance of coaching and instructional structures reinforces the argument that VR should be viewed not as a replacement but as a complement to traditional training (20). Moreover, the social and institutional dynamics identified in this study connect with findings from music and cognitive learning research, suggesting that transfer is embedded within cultural and organizational contexts (6). Finally, the reported benefits of perceptual-motor coupling, anticipation, and memory consolidation align with computational and neuroscientific models of motor learning (1, 9).

Overall, this study contributes to a growing interdisciplinary conversation on how technology-mediated learning translates into embodied performance. By situating the voices of athletes, coaches, and specialists within this theoretical landscape, it provides empirical evidence for both the promise and the limitations of VR in racket sport training.

Despite offering important insights, this study is not without limitations. First, the sample size was relatively small, consisting of 19 participants from the United States, which may limit the generalizability of findings to other cultural or sporting contexts. Second, the reliance on self-reported experiences may have introduced recall or desirability bias, as participants may have emphasized positive aspects of VR training. Third, the study focused exclusively on racket sports, and findings may not directly transfer to sports with different perceptual-motor demands such as team-based invasion games or endurance events.

Finally, as a qualitative inquiry, this study did not measure actual performance transfer quantitatively, leaving questions about the extent of behavioral change unanswered.

Future studies should adopt mixed-methods approaches to triangulate qualitative perceptions with quantitative measures of skill transfer, such as on-field performance metrics or biomechanical analyses. Longitudinal research would be valuable to examine the durability of VR-trained skills over extended competitive seasons. Cross-cultural investigations could reveal how cultural differences in technology adoption influence transfer. Additionally, experimental manipulations of VR fidelity—such as systematically varying haptic or audio-visual realism—could identify which design features most directly facilitate transfer. Finally, comparative studies across sports with differing motor demands could clarify the boundaries of VR's effectiveness.

From a practical standpoint, coaches and sport organizations should integrate VR as a complementary tool rather than a standalone replacement for on-field training. Emphasis should be placed on fidelity, particularly in replicating sensory cues and contextual stressors. Athletes should be guided to maintain a transfer mindset, actively reflecting on connections between VR practice and real matches. Coaches should remain actively involved, offering feedback and embedding VR into periodized training programs. Institutions and clubs should support adoption with resources and cultural endorsement, while athletes should use VR strategically for safe repetition, anticipation training, and psychological preparation.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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References

1. Zhang X, Song Z, Shen X, Chen S, Huang Y, Wang Y. Aligning Neural Population Patterns Facilitates Motor Learning Transfer. 2025. doi: 10.1101/2025.05.16.654614.

2. Yun J-E, Im C-H, Park J-H. Effects of Repetitive Practice on Motor Learning and Adaptability in Foot Position Control for Cerebellar Ataxia. International Journal of Rehabilitation Research. 2025. doi: 10.1097/mrr.0000000000000670.

3. Sun Y, Jang D, Park SB. Perception-Action Coupling During Discriminative Interceptive Actions. Frontiers in Psychology. 2025;16. doi: 10.3389/fpsyg.2025.1526153.

4. Modchalingam S, King AJ, Hart BM, Henriques DYP. Visual Properties of Action Consequences and Not Environments Affect Context-Specific Motor Learning. Journal of Neurophysiology. 2025;133(4):1176-90. doi: 10.1152/jn.00268.2024.

5. Yamaguchi M. Transfer Asymmetry: Tversky's Contrast Model of Similarity for Human Perceptual-Motor Learning. 2024. doi: 10.31219/osf.io/d78qs.

6. Worschech F, Passarotto E, Losch H, Oku T, Lee A, Altenmüller E. What Does It Take to Play the Piano? Cognito-Motor Functions Underlying Motor Learning in Older Adults. Brain Sciences. 2024;14(4):405. doi: 10.3390/brainsci14040405.

7. Tomlin KB, Johnson BP, Westlake KP. Age-Related Differences in Motor Skill Transfer With Brief Memory Reactivation. Brain Sciences. 2024;14(1):65. doi: 10.3390/brainsci14010065.

8. Longman CS, Milton F, Wills AJ. Transfer of Strategic Task Components Across Unique Tasks That Share Some Common Structures. Quarterly Journal of Experimental Psychology. 2024;77(10):2000-22. doi: 10.1177/17470218231221046.

9. Kim W, Ortíz EV. Algorithmic Implementation of Visually Guided Interceptive Actions: Enhancing Motion Perception in Virtual and Augmented Reality Systems. Int J Med Net. 2024;2(10):01-17. doi: 10.33140/ijmn.02.10.03.

10. Kim W, Araújo D, Choi MY, Vette AH, Ortíz EV. Algorithmic Implementation to Visually Controlled Interception: Harmonic Ratios and Stimulation Invariants. 2024. doi: 10.20944/preprints202405.1930.v1.

11. Kim W, Araújo D, Choi MY, Vette AH, Ortíz EV. Algorithmic Implementation of Visually Guided Interceptive Actions: Harmonic Ratios and Stimulation Invariants. Algorithms. 2024;17(7):277. doi: 10.3390/a17070277.

12. Antonioni A, Cellini N, Baroni A, Fregna G, Lamberti N, Koch G, et al. Characterizing Practice-Dependent Motor Learning After a Stroke. Neurological Sciences. 2024;46(3):1245-55. doi: 10.1007/s10072-024-07815-y.

13. Barzyk P, Grüber M. Motor Learning in Golf—a Systematic Review. Frontiers in Sports and Active Living. 2024;6. doi: 10.3389/fspor.2024.1324615.

14. Beißel P, Künzell S. Task Integration in Complex, Bimanual Sequence Learning Tasks. Psychological Research. 2023;88(1):207-21. doi: 10.1007/s00426-023-01848-2.

15. Bera K, Shukla A, Bapi RS. Cognitive and Motor Learning in Internally-Guided Motor Skills. Frontiers in Psychology. 2021;12. doi: 10.3389/fpsyg.2021.604323.

16. Feulner B, Postin D, Schwiedrzik CM, Pooresmaeili A. Previous Motor Actions Outweigh Sensory Information in Sensorimotor Statistical Learning. Eneuro. 2021;8(5):ENEURO.0032-21.2021. doi: 10.1523/eneuro.0032-21.2021.

17. Jäger AT, Huntenburg JM, Tremblay S, Schneider U, Grahl S, Huck J, et al. Motor Sequences; Separating the Sequence From the Motor. A Longitudinal rsfMRI Study. Brain Structure and Function. 2021;227(3):793-807. doi: 10.1007/s00429-021-02412-7.

18. James M. Teaching for Transfer of Second Language Learning: A Proposed Research Agenda. Language Teaching. 2024:1-16. doi: 10.1017/s0261444824000314.

19. Keller M, Roth R, Achermann S, Faude O. Learning a New Balance Task: The Influence of Prior Motor Practice on Training Adaptations. European Journal of Sport Science. 2022;23(5):809-17. doi: 10.1080/17461391.2022.2053751.

20. Maudrich T, Kandt H, Ragert P, Kenville R. Whole-Body Sensorimotor Skill Learning in Football Players: No Evidence for Motor Transfer Effects. Plos One. 2022;17(7):e0271412. doi: 10.1371/journal.pone.0271412.

21. Paparella G, Riggi MD, Cannavacciuolo A, Colella D, Costa D, Birreci D, et al. Relationship Between the Interlimb Transfer of a Visuomotor Learning Task and Interhemispheric Inhibition in Healthy Humans. Cerebral Cortex. 2023;33(12):7335-46. doi: 10.1093/cercor/bhad042.

22. Sánchez-Moncada I, Concha L, Merchant H. Pre-Supplementary Motor Cortex Mediates Learning Transfer From Perceptual to Motor Timing. Journal of Neuroscience. 2023:JN-RM-3191-20. doi: 10.1523/jneurosci.3191-20.2023.

23. Siqi-Liu A, Egner T. Task Sets Define Boundaries of Learned Cognitive Flexibility in List-Wide Proportion Switch Manipulations. 2022. doi: 10.31234/osf.io/uype2.

24. Tseng G, Kerner H, Rolnick D. TIML: Task-Informed Meta-Learning for Agriculture. 2022. doi: 10.48550/arxiv.2202.02124.

25. Xing X, Saunders JA. Different Generalization of Fast and Slow Visuomotor Adaptation Across Locomotion and Pointing Tasks. Experimental Brain Research. 2021;239(9):2859-71. doi: 10.1007/s00221-021-06112-w.

26. Yin C. The Savings in Motor Adaptation: Implications on Sports Training. Destech Transactions on Economics Business and Management. 2021(eeim). doi: 10.12783/dtem/eeim2020/35291.

27. Monajatipoor M, Rouhsedaghat M, Li LH, Chien A, Kuo CCJ, Scalzo F, et al. BERTHop: An Effective Vision-and-Language Model for Chest X-Ray Disease Diagnosis. 2021:3327-36. doi: 10.1109/iccvw54120.2021.00372.