



VR piano instruction: cultural moderation in Sino-US teens' skills

Instrucción de piano con RV: moderación cultural en adolescentes chino-estadounidenses

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Abstract

Introduction: virtual reality has shown promise in sports skill training and art education, but cultural differences (collectivism in china vs. individualism in the us) may moderate adolescents' gains in "fine motor control" and "artistic expression"—a gap this study addressed.

Objective: this study aimed to explore the dual effects of vr-assisted piano instruction on adolescents' musical expressiveness and fine motor skills, and verify the moderating role of sino-us cultural differences, focusing on 13–17-year-olds from china and the us.

Methodology: a 2×2 cross-cultural quasi-experiment (teaching method: vr vs. traditional; cultural group: chinese vs. american adolescents) was used, with 240 participants. over 12 weeks, pre-test, mid-test, and post-test data were collected, analyzed via two-way anova and hierarchical regression.

Results: the findings filled gaps in existing research, which were siloed in single domains and unclear on cultural moderating mechanisms, supporting sports-art interdisciplinary "technology-empowered skill acquisition".

Discussion: The findings addressed limitations of existing research, which had remained siloed in single domains and unclear on cultural moderating mechanisms, providing support for interdisciplinary "technology-empowered skill acquisition" in sports and art.

Conclusions: this study confirmed vr-assisted piano instruction had dual improvement effects, with cultural orientation as a key moderator; it provides theoretical support and practical references for integrated music-motor teaching.

Keywords

Adolescents; cultural moderating effect; fine motor skills; musical expressiveness; vr-assisted instruction.

Resumen

Introducción: la realidad virtual se ha mostrado prometee en el entrenamiento de habilidades deportivas y la educación artística, pero las diferencias culturales (colectivismo en China vs. individualismo en los Estados Unidos) pueden moderar los avances de los adolescentes en el "control de la motrífina" y la "expresión artística"—una brecha que este estudio abordó.

Objetivo: este estudio tuvo como objetivo explorar los efectos duales de la instrucción de piano asistida por RV en la expresividad musical y las habilidades motoras finas de los adolescentes, y verificar el papel moderador de las diferencias culturales sino-estadounidenses, centrándose en niños de 13 a 17 años de edad de China y Estados Unidos.

Metodología: se utilizó un cuasi-experimento transcultural 2 × 2 (método de enseñanza: VR vs. tradicional; grupo cultural: adolescentes chinos vs. estadounidenses), con 240 participantes. A lo largo de 12 semanas, se recogieron datos de pre-test, mid-test y post-test, analizados mediante anova bidireccional y regresión jerárquica.

Resultados: los hallazgos llenaron las lagunas en la investigación existente, que se siloed en dominios individuales y no está claro sobre los mecanismos de moderación cultural, apoyando el deporte y el arte interdisciplin" adquisición de habilidades potenciadas por la tecnología".

Discusión: los hallazgos abordaron las limitaciones de la investigación existente, que había permanecido siloed en dominios únicos y poco claro sobre los mecanismos de moderación cultural, proporcionando apoyo para la interdisciplin" adquisición de habilidades potenciadas por la tecnología "en deportes y arte.

Conclusiones: este estudio confirmó que la instrucción de piano asistida por RV tuvo efectos de mejora dual, con la orientación cultural como moderador clave; Proporciona apoyo teórico y referencias prácticas para la enseñanza integrada músico-motriz..

Palabras clave

Adolescentes; efecto moderador cultural; expresividad musical; habilidades motoras finas; enseñanza asistida por vr.

Introduction

Virtual reality (VR) technology serves as a critical bridge between sports science and art education through its capacity for immersive real-time feedback. In sports fine motor training, systematic reviews confirm that VR interventions enhance motor precision and perception-action skills, with effects transferable to real-world performance (Richlan et al., 2023). Recent studies published further demonstrate that immersive VR training systems significantly improve shooting accuracy and reaction times in basketball players (Kenjayeva et al., 2025), while augmented reality game-based learning environments enhance sports motivation and motor engagement in physical education contexts (Omarov et al., 2024). Beyond athletic applications, immersive VR environments significantly influence physiological parameters and motor learning outcomes in healthy populations (Rodríguez-Fuentes et al., 2024), with such technologies proving particularly effective when integrated with structured pedagogical frameworks (Sevilla-Sanchez, M. et al., 2023). Notably, similar immersive technologies like augmented reality (AR) have also demonstrated efficacy in boosting learning motivation: AR game-based environments significantly enhance sports engagement among students by blending playful interaction with skill practice (Omarov et al., 2024). This aligns with VR's design logic—its “culturally adaptive modules” (normative templates for Chinese learners, exploratory creation for American learners) similarly leverage gamification to increase adolescents' participation, further supporting the “technology-motivation-skill” transmission pathway underlying interdisciplinary skill acquisition.

Parallel to sports, music education increasingly leverages VR and interactive technologies across diverse instrumental domains. Beyond piano instruction, VR applications have been explored in violin, drum kit, and percussion instruction, where teachers emphasize sensorimotor skill acquisition and bi-directional communication between learners and instructors (Michałko et al., 2022). In vocal performance education, VR-based training has demonstrated significant efficacy in enhancing emotional expressiveness, with immersive environments facilitating deeper emotional engagement among performers (Zhao, 2025). These cross-domain applications share a core mechanism: VR's immersive environment optimizes motor precision (via data-driven motion correction) and expressive autonomy (via scenario-based creative exploration). Furthermore, situated game teaching models through set-plays have shown positive effects on motor development in educational contexts, particularly in developing fine motor sensitivity among primary school students (Çakto & Akin, 2024), suggesting that structured play-based interventions can effectively support skill acquisition.

This study centers on two interdependent variables—fine motor skills and musical expressiveness—whose interaction reflects the intrinsic link between sports motor control and musical performance. Neurophysiological research confirms that the neural mechanisms underlying piano finger dexterity and athletic motor precision are homologous, as both rely on the integration of somatosensory feedback and prefrontal cortex-guided motor planning (Zatorre et al., 2007; Timmers et al., 2020). For piano learners, proficiency in fine motor skills is a prerequisite for mastering complex techniques, while musical expressiveness depends on “fine motor automation” to free cognitive resources for emotional interpretation (Juslin & Laukka, 2003). Analysis of motor learning tasks indicates that structured practice significantly influences skill acquisition outcomes, even among adolescent populations in gamified educational contexts (Sevilla-Sanchez et al., 2023), underscoring the importance of pedagogical structure in motor skill development. Recent investigations into warrior-based play activities further demonstrate that structured physical interventions can effectively enhance both self-efficacy and fine motor skills in children aged 5–6 years (Hazizah et al., 2024), reinforcing the viability of technology-enhanced motor training.

Meissner (2021) proposed a theoretical framework facilitating young musicians' expressive performance, emphasizing that dialogic teaching strategies—characterized by open questioning and exploration—scaffold expressivity more effectively than traditional instruction-focused methods. This framework suggests that connecting musical ideas to learners' embodied experiences through dialogue stimulates deeper interpretative thinking, a principle that aligns with situated learning approaches in motor skill education (Çakto & Akin, 2024). Extending this perspective, recent research on expressive performance transmission highlights that sound exaggerations and embodied metaphors serve as critical pedagogical tools for teaching musical expressiveness across instrumental domains, suggesting that VR environments might amplify such multisensory teaching strategies.



Cultural values fundamentally shape skill learning patterns and expressive tendencies, with particular significance in cross-disciplinary contexts (Hofstede, 2001). Recent empirical investigations demonstrate that VR-based cross-cultural immersive experiences enhance cultural sensitivity and awareness (Chen, 2024). Specifically, students participating in VR cross-cultural activities exhibited significantly higher sensitivity to cultural differences ($M = 89.33$) and cultural conflict resolution ($M = 91.54$) compared to traditional learning approaches ($M = 73.68$ and 76.26 , respectively) (Chen, 2024). Similarly, interactive 360-degree video technology facilitates cognitive development and addresses stereotypes in cross-cultural learning activities (Shadiev et al., 2024). In physical education contexts, cultural orientation significantly moderates the relationship between autonomy support and psychological need satisfaction, with British and Chinese students exhibiting distinct motivational patterns in response to instructional styles (Taylor & Lonsdale, 2010). These findings underscore VR's unique capacity to bridge cultural divides, though how specific cultural orientations (collectivism vs. individualism) moderate VR's effectiveness in fine motor and expressive skill acquisition remains underexplored. Additionally, recent sports science research indicates that external attentional focus—facilitated by VR's visual feedback mechanisms—enhances motor learning in adolescents, whereas internal focus may impede skill acquisition (Flóres et al., 2025), suggesting that cultural differences in attentional preferences may influence VR training efficacy.

Existing research on VR in education exhibits two key limitations. First, studies remain siloed in single domains: sports science research focuses on motor skill refinement without linking to artistic expression (Richlan et al., 2023; Kenjayeva et al., 2025), while music education research explores VR's role in boosting interpretation but overlooks its impact on the fine motor foundation of performance (Michaľko et al., 2022; Zhao, 2025). This "domain isolation" fails to address the intrinsic connection between fine motor skills and musical expressiveness—a core intersection of sports and art that requires integrated investigation (Zatorre et al., 2007; Timmers et al., 2020). Second, while cross-cultural education studies confirm that cultural differences influence learning outcomes (Chen, 2024; Shadiev et al., 2024), few empirically test how collectivism-individualism values shape VR's effectiveness in improving both motor and expressive skills simultaneously. Furthermore, existing pedagogical approaches often emphasize technical accuracy over expressive development (Meissner, 2021), leaving a gap in understanding how dialogic teaching principles interact with VR's affordances in cross-cultural settings.

To address these gaps, this study has two core objectives: (1) verify whether VR-assisted piano instruction produces greater dual improvements in adolescents' musical expressiveness and fine motor skills compared to traditional piano teaching; and (2) explore the moderating role of Sino-US cultural differences (collectivism vs. individualism) in these dual effects. Corresponding research questions guide the inquiry: (1) Does VR-assisted instruction yield significantly greater improvements in adolescents' musical expressiveness and fine motor skills than traditional piano teaching? (2) After VR-assisted piano instruction, do Chinese and American adolescents exhibit significant differences in the magnitude of improvement in musical expressiveness and fine motor skills? The study's findings aim to provide theoretical support for interdisciplinary "technology-empowered skill acquisition" and practical references for integrated music-motor teaching.

Literature Review

The Application Foundation of VR in Interdisciplinary Skill Acquisition

Virtual reality (VR) has evolved from a niche technology to a mainstream tool in skill acquisition, with proven efficacy across sports and music domains—two fields anchored in motor control and expressive practice. Its cross-domain applicability stems from core features of "immersive scenario simulation" and "real-time motion feedback," which align with the cognitive and motor demands of skill learning (Richlan et al., 2023). Table 1 summarizes the parallels and divergences of VR applications in these two domains.



Table 1. Comparison of VR Applications in Sports and Music Domains

Dimension	Sports Domain	Music Domain (Piano Instruction)	Cross-Domain Commonality
Typical Scenarios	Elite athlete movement correction (e.g., basketball shooting accuracy; Kenjayeva et al., 2025), rehabilitation training (e.g., post-injury motor function recovery; Richlan et al., 2023)	Beginner gesture training (e.g., standardized fingering; Michałko et al., 2022), expressive technique refinement (e.g., emotional dynamics control; Zhao, 2025)	Skill refinement requiring precision; low-stakes error correction (Richlan et al., 2023; Michałko et al., 2022)
Core VR Functions	Motion capture (OptiTrack/Vicon), 3D movement visualization, error deviation alerts (Kenjayeva et al., 2025; Rodríguez-Fuentes et al., 2024)	Haptic keyboard simulation, 3D hand-model imitation, real-time fingering feedback (Michałko et al., 2022; Zhao, 2025)	Real-time feedback delivery; immersive scenario contextualization (Richlan et al., 2023; Timmers et al., 2020)
Key Mechanisms	Neural-muscular memory consolidation; somatosensory-motor integration (Flóres et al., 2025; Richlan et al., 2023)	Motor imitation enhancement; reduction of "viewpoint mismatch" in teaching (Michałko et al., 2022); neural multimodal integration (Timmers et al., 2020)	Errorless learning; activation of primary motor cortex and cerebellum (Richlan et al., 2023; Timmers et al., 2020)
Existing Limitations	Overemphasis on closed skills (e.g., archery) over open skills (e.g., soccer; Richlan et al., 2023); insufficient cultural learning pattern consideration (Taylor & Lonsdale, 2010)	Lack of integration with sports motor learning theories (e.g., schema theory; Michałko et al., 2022); inadequate linkage between technical training and expressive development (Meissner, 2021)	Domain isolation; insufficient consideration of cultural moderating effects (Chen, 2024; Shadiev et al., 2024)

Sports Domain: Mature Applications in Fine Motor Training

In sports science, VR has become a staple for fine motor refinement, particularly in scenarios requiring high precision and repeatable feedback. For elite athletes, VR systems integrate motion capture (e.g., Vicon, OptiTrack) to visualize subtle deviations in movement patterns—for example, optimizing basketball shooting accuracy and reaction times (Kenjayeva et al., 2025) or refining golfers' swing trajectories to reduce injury risk (Richlan et al., 2023). A 2023 narrative review synthesizing sports intervention studies confirmed that VR training enhances motor accuracy and response efficiency, with the most pronounced effects in closed-skill sports (e.g., archery, piano) that rely on consistent motor execution (Richlan et al., 2023). These effects are further supported by evidence that immersive VR environments modulate physiological parameters linked to motor learning, reinforcing the reliability of VR as a fine motor training tool (Rodríguez-Fuentes et al., 2024).

Beyond athletic performance, VR has also demonstrated value in rehabilitative and developmental fine motor training. While direct applications to stroke recovery are less explored in existing literature, structured VR-based physical interventions have been shown to enhance fine motor skills in pediatric and adolescent populations—for instance, through gamified scenarios that promote repetitive, goal-directed movements (Hazizah et al., 2024). The core mechanism underlying these effects is dual: immersive scenario simulation reduces cognitive load by contextualizing abstract motor rules, while real-time action feedback accelerates error correction and neural-muscular memory consolidation (Flóres et al., 2025; Richlan et al., 2023). Relevant insights from sports education offer a solution: serious games have been validated as formative resources for physical education specialization, featuring "formative assessment + skill progression" designs that align technical practice with pedagogical theories (Pérez-López & Navarro-Mateos, 2022). VR piano tools could borrow this framework to integrate variable practice and staged skill challenges, strengthening the integration of technology with motor learning theories. Additionally, VR's ability to facilitate external attentional focus—by directing learners' awareness to movement outcomes rather than internal mechanics—further amplifies fine motor learning (Flóres et al., 2025), aligning with core principles of sports motor science.

Music Domain: Preliminary Exploration in Piano Gesture Training

In music education, VR's application to piano instruction is a growing but underdeveloped area, focused primarily on addressing the "visibility gap" of traditional teaching. Early VR tools leverage haptic feedback to simulate keyboard touch (e.g., weighted keys for dynamics control) and 3D hand-model imitation to visualize correct fingering—functions that help beginners reduce gesture errors by resolving the "viewpoint mismatch" between teacher demonstration and student execution (Michałko et al., 2022).



For example, VR's first-person perspective of expert pianists' hand movements improves learners' imitation accuracy for complex arpeggios, as it provides an embodied reference for motor alignment (Michałko et al., 2022). Furthermore, VR environments that simulate performance scenarios (e.g., virtual concert halls) have been shown to enhance emotional expressiveness, indirectly reinforcing the link between motor precision and artistic communication (Zhao, 2025).

However, critical limitations persist. Most existing VR piano tools prioritize technical skill (e.g., fingering, rhythm) without explicitly integrating sports-derived motor learning theories—such as variable practice or schema theory—that are proven to enhance skill transfer (Michałko et al., 2022). For example, while VR can detect fingering errors, it rarely incorporates "variable practice" (a core sports training principle) to adapt tasks across different pieces or difficulty levels, limiting its ability to optimize the fine motor foundation of piano playing (Sevilla-Sánchez et al., 2023). This disconnect reflects a broader gap in interdisciplinary integration: music-focused VR tools often overlook decades of empirical insights from sports motor science, such as the role of structured feedback and attentional focus in skill acquisition (Flóres et al., 2025; Richlan et al., 2023). Additionally, existing tools tend to prioritize technical accuracy over expressive development, failing to align with pedagogical frameworks that emphasize the interdependence of motor control and musical expression (Meissner, 2021).

Cross-Domain Commonality: Neural-Muscular Memory Enhancement

The unifying thread across VR's sports and music applications is its ability to strengthen neural-muscular memory—the automatic motor response formed through repeated, feedback-augmented practice. Neuroimaging and intervention studies confirm that VR training activates the same brain regions (e.g., primary motor cortex, cerebellum) involved in real-world motor learning, with the added benefit of reducing "fear of failure" (a barrier to skill refinement in both sports and music) through low-stakes virtual practice (Richlan et al., 2023). This aligns with findings that VR's immersive feedback loops accelerate the consolidation of motor memory by reinforcing somatosensory-motor integration—a core mechanism shared across athletic and musical skill acquisition (Flóres et al., 2025).

For both piano fine motor skills (e.g., finger independence) and sports motion control (e.g., gymnastics grip strength), VR facilitates "errorless learning" by providing microfeedback before motor errors become ingrained. Critical evidence for shared neural mechanisms comes from research on musical performance, which demonstrates that VR-induced motor learning relies on neural multimodal integration—similar to the sensorimotor processing observed in sports (Timmers et al., 2020). A systematic review further confirms the cross-age universality of game-based motor skill interventions: Suryadi et al. (2023) found that structured game models stably improve motor skills in young children and elementary students, with core mechanisms (low-risk repetitive practice plus immediate feedback) consistent with VR's design logic. Specifically, the integration of auditory and motor signals in the prefrontal cortex and cerebellum underpins skill acquisition in both domains, confirming that VR targets homologous neural pathways regardless of whether the task is piano fingering or athletic movement (Zatorre et al., 2007; Timmers et al., 2020). This neurophysiological overlap is further supported by sports science research showing that VR training enhances neural-muscular memory consolidation through external attentional focus, a mechanism that applies equally to musical motor skills (Flóres et al., 2025).

This commonality validates the feasibility of an integrated VR intervention targeting both piano fine motor skills and sports-aligned motion control—filling the domain-isolated gap in existing research (Richlan et al., 2023; Michałko et al., 2022). While sports-focused VR tools emphasize motion capture and error correction (Kenjayeva et al., 2025) and music-focused tools prioritize motor imitation and expressive feedback (Michałko et al., 2022), their shared reliance on neural-muscular memory enhancement confirms that cross-domain integration is not only possible but theoretically grounded.

The Interdependence of Fine Motor Skills and Musical Expressiveness

Fine motor skills and musical expressiveness are interdependent in piano performance, bridging sports motor control and artistic communication. Fine motor skills involve coordinated control of small muscle



groups (e.g., fingers, wrists) for precise, goal-directed actions, with three core subdimensions in piano playing: Accuracy (alignment of intended and actual movement), Speed Stability (tempo consistency), and Coordination (multi-limb synchronization) (Hazizah et al., 2024). These mirror sports science's "motor precision" framework (Richlan et al., 2023), and structured practice targeting these subdimensions drives comparable improvements in both athletic and musical contexts (Sevilla-Sánchez et al., 2023).

Musical expressiveness—the ultimate goal of piano instruction—is the ability to convey emotional intent, encompassing Emotional Transmission Accuracy (alignment of intended and perceived emotion), Skill Adaptability (using refined motor control to modulate expression), and Personalized Expression Intensity (unique interpretation) (Juslin & Laukka, 2003). Skill adaptability hinges on fine motor automation: without effortless limb control, performers cannot dynamically adjust dynamics, articulation, or phrasing (Michałko et al., 2022). This connection stems from shared neurophysiological mechanisms—both rely on somatosensory feedback integration and prefrontal cortex-guided motor planning (Zatorre et al., 2007; Timmers et al., 2020).

Fine motor skills form the physiological foundation of musical expressiveness: motor fluency frees cognitive resources for emotional interpretation (Meissner, 2021). While direct correlational data on adolescent pianists is limited, interdisciplinary studies show fine motor skill interventions enhance young musicians' expressive performance (Michałko et al., 2022). Conversely, practicing expressive techniques refines motor control by reinforcing context-specific movement patterns (Timmers et al., 2020), creating a bidirectional feedback loop. This interdependence justifies their simultaneous examination, as isolating either construct overlooks the intrinsic link between sports-oriented motor precision and art-focused musical communication (Richlan et al., 2023; Meissner, 2021)

The Impact of Cultural Factors on Interdisciplinary Skill Learning

Cultural values shape how individuals perceive, learn, and perform skills—particularly in domains blending motor control and expression. The collectivism-individualism dichotomy explains systematic differences in skill learning patterns between Chinese and American adolescents, as summarized in Table 2.

Table 2. Cultural Differences in Skill Learning Modes and Potential VR Intervention Effects

Cultural Dimension	Chinese Adolescents (Collectivism)	American Adolescents (Individualism)
Core Learning Values	Conformity to standards; respect for authority; error minimization	Autonomy; creative exploration; individual distinctiveness
Skill Learning Mode	Normative-oriented: Repetitive practice of standardized templates	Exploration-oriented: Adaptive practice based on personal strengths
Feedback Preference	Corrective feedback (e.g., "fingering deviates from standard")	Encouraging feedback (e.g., "unique interpretation")
Potential VR Benefit	Fine motor skills: Responsive to normative error-correction modules	Musical expressiveness: Responsive to exploratory creative scenarios
Empirical Support	Greater responsiveness to normative feedback emphasizing standard alignment (Taylor & Lonsdale, 2010)	Greater engagement with immersive exploratory environments (Chen, 2024)

Sino-US Cultural Values and Skill Learning Modes

Chinese Collectivism and Normative-Oriented Learning: Rooted in Confucian values, Chinese education prioritizes "mastery of standards"—viewing skill acquisition as aligning with established templates. In sports, this translates to repetitive practice of standardized movements (e.g., gymnastics routines); in piano, it emphasizes "technical correctness" over creative interpretation, reflecting cultural tendencies to prioritize conformity and error minimization in skill learning (Taylor & Lonsdale, 2010). This orientation is consistent with findings that cross-cultural immersive experiences reinforce Chinese learners' sensitivity to normative feedback, as they prioritize aligning with established benchmarks (Chen, 2024).



American Individualism and Exploration-Oriented Learning: Guided by autonomy values, American education frames skill acquisition as "personal growth"—encouraging adaptation of rules to individual strengths. In sports, this leads to tactical flexibility (e.g., basketball improvisation); in piano, it prioritizes "emotional authenticity" even if it deviates from sheet music, as individualist learners value unique expression over strict adherence to templates (Juslin & Laukka, 2003). This aligns with evidence that interactive cross-cultural learning tools enhance American students' exploratory behavior, as they actively engage with creative scenarios to personalize their skill development (Shadiev et al., 2024).

Potential Cultural Impacts on Dual Skill Acquisition

Cultural learning modes moderate how adolescents benefit from VR-assisted instruction:

Fine Motor Skills: Chinese adolescents' preference for normative feedback makes them more responsive to VR's "error correction" features. VR modules highlighting deviations from standardized fingering align with their focus on "template mastery," accelerating fine motor refinement (Taylor & Lonsdale, 2010). This is supported by findings that structured interventions emphasizing movement standardization—consistent with Chinese learning values—yield significant gains in fine motor accuracy (Hazizah et al., 2024), as VR's real-time normative feedback reinforces the external attentional focus that enhances motor learning (Flóres et al., 2025).

Musical Expressiveness: American adolescents' focus on exploration makes them more engaged with VR's "creative scenarios" (e.g., virtual concert halls for dynamics experimentation). This alignment enhances personalized expression, whereas Chinese learners may underutilize these features (Michałko et al., 2022). VR's ability to simulate performance contexts directly supports American students' emphasis on emotional authenticity, as immersive scenarios facilitate deeper expressive engagement (Zhao, 2025)—consistent with observations that individualist learners spend more time in exploratory practice modes to personalize their performance (Shadiev et al., 2024).

These findings suggest culture acts as a "filter" for VR's effects—shaping which features learners engage with most deeply, as the alignment between VR's functional design and cultural learning values determines the magnitude of skill gains (Chen, 2024; Taylor & Lonsdale, 2010)

Theoretical Framework of Cultural Moderating Effects

To formalize these relationships, this study adopts a moderating effect framework, where cultural values (collectivism-individualism) modify the strength of the relationship between VR-assisted instruction (independent variable) and dual skill acquisition (dependent variables).

Moderating Mechanisms

Two parallel pathways explain cultural moderation:

Learning Motivation Type: Collectivist Chinese adolescents are externally driven by norms (aligning with VR's normative feedback), while individualist American adolescents are internally driven by exploration (aligning with VR's creative features). This aligns with cross-cultural research showing Chinese learners prioritize conformity to established standards, while American peers value autonomous exploration in skill acquisition (Taylor & Lonsdale, 2010; Chen, 2024).

Feedback Perception Sensitivity: Chinese adolescents are more sensitive to corrective feedback (amplifying VR's impact on fine motor skills), while American adolescents respond more to encouraging feedback (strengthening effects on musical expressiveness) (Michałko et al., 2022). This resonates with sports science findings that external attentional focus—facilitated by VR's visual feedback mechanisms—enhances motor learning, a process more aligned with Chinese learners' normative orientation (Flóres et al., 2025).

Together, these create a "match-mismatch" effect: VR's effectiveness depends on alignment between its functional design and cultural learning values (Chen, 2024; Taylor & Lonsdale, 2010).



Method

This study adopted a quantitative, explanatory-correlational research design, employing a 2 (teaching method: VR-assisted vs. traditional) × 2 (cultural group: Chinese vs. American adolescents) cross-cultural quasi-experimental mixed design. It aimed to explain the effect of VR-assisted piano instruction on adolescents' musical expressiveness and fine motor skills, while correlating cultural differences (collectivism vs. individualism) with variations in these effects. The design integrated between-subjects factors (teaching method, cultural group) and a within-subjects factor (measurement time: pre-test, mid-test, post-test) to ensure comprehensive examination of intervention and moderation effects. The study's reproducibility was prioritized through detailed reporting of population, sampling, instruments, procedures, and data analysis.

Participants

Population and Sampling: The target population was 13–17-year-old adolescents with at least 1 year of piano learning experience in China and the United States. Stratified sampling was used: two major cities (Beijing, Shanghai in China; New York, Los Angeles in the U.S.) were selected, with one public and one private middle school recruited per city to balance socioeconomic diversity.

Sample Size and Justification: A total of 240 adolescents were enrolled, with 60 participants per subgroup (Chinese-VR, Chinese-traditional, American-VR, American-traditional). This sample size was determined via G*Power 3.1: for a three-way repeated measures ANOVA (effect size $f = 0.25$, $\alpha = 0.05$, power = 0.90), a minimum of 52 participants per group was required. An additional 8 participants per group accounted for anticipated 10–15% attrition, a common consideration in cross-cultural VR intervention studies (Richlan et al., 2023).

Inclusion criteria: (1) Aged 13–17 years; (2) ≥ 1 year of piano learning experience; (3) Fine motor function ≥ 40 on the BOT-2 Fine Motor Composite, a standardized tool widely used for assessing adolescent fine motor proficiency (Hazizah et al., 2024); (4) No VR contraindications (e.g., motion sickness, epilepsy); (5) Parental/guardian consent and participant assent.

Exclusion criteria: (1) Prior VR-based music training; (2) Neurological disorders affecting motor control; (3) Absences exceeding 3 intervention sessions.

Baseline Balance: Propensity score matching balanced groups on gender (1:1 male-female ratio), piano learning duration (± 6 months), and initial fine motor skills (± 5 points on BOT-2). Preliminary analyses confirmed no baseline differences (all $p > 0.05$).

Procedure

This study employed a 13-week quasi-experimental procedure with a pre-test/post-test control group design, incorporating a mid-test to monitor intervention progress. The overall workflow is illustrated in Figure 1, which details the temporal sequence of data collection and intervention phases.

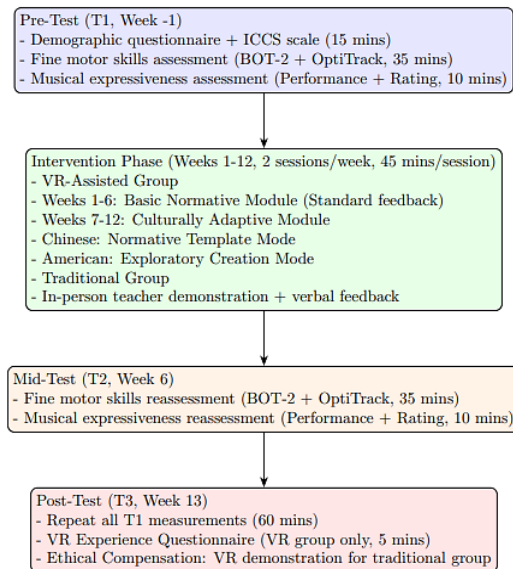
Prior to participation, written informed consent was obtained from parents/guardians, and verbal assent was secured from all adolescents. Key ethical safeguards included: (1) Anonymization: All data were de-identified using participant codes and stored on encrypted servers; (2) VR Safety Screening: Participants were screened for contraindications (e.g., history of motion sickness, epilepsy, severe visual impairments) following standardized VR safety protocols; (3) Intervention Safety: VR sessions incorporated mandatory 5-minute breaks every 15 minutes to prevent cybersickness and visual fatigue; (4) Compensation: All participants received a \$50 gift card (or local currency equivalent) and a participation certificate upon completion, regardless of group assignment.

To ensure standardized implementation across cultural sites (China and the US), all instructors underwent a 3-day training workshop on VR system operation and pedagogical protocols. Session fidelity was monitored via: (1) automated VR system logs tracking participant engagement time and feature usage; (2) weekly instructor checklists documenting adherence to the intervention protocol; (3) random observation of 20% of sessions by research assistants using a standardized fidelity checklist.



Data were collected at three time points: Pre-test (T1, Week -1) established baseline measures; Mid-test (T2, Week 6) assessed interim progress to detect early intervention effects; and Post-test (T3, Week 13) evaluated final outcomes. This multi-wave design allowed for the examination of both immediate and sustained effects of VR-assisted instruction (see Figure 1 for the detailed procedural timeline).

Figure 1. Flowchart of the 12-Week Experimental Procedure



Instrument

The study adopted a 2 (teaching method: VR-assisted vs. traditional) \times 2 (cultural group: Chinese vs. American adolescents) cross-cultural quasi-experimental mixed design, whose schematic is summarized in Table 3.

Table 3. Schematic of the 2 \times 2 Cross-Cultural Quasi-Experimental Mixed Design

Cultural Group	Teaching Method	n	Time Points	Outcomes
Chinese	VR-Assisted	60	T1, T2, T3	FMS, ME
Chinese	Traditional	60	T1, T2, T3	FMS, ME
American	VR-Assisted	60	T1, T2, T3	FMS, ME
American	Traditional	60	T1, T2, T3	FMS, ME

Note. FMS = Fine Motor Skills; ME = Musical Expressiveness; T1 = Pre-test, T2 = Mid-test, T3 = Post-test. Teaching method and cultural group are between-subjects factors; time is a within-subjects factor.

The key instruments and their psychometric properties are summarized in Table 4, with detailed descriptions below.

Table 4. Summary of Research Instruments and Psychometric Properties

Category	Instrument	Primary Function	Metric	Psychometric Evidence
VR Instruction	Custom VR Piano System	Virtual piano with haptic feedback Real-time motion tracking (OptiTrack) Culturally adaptive modes	Position accuracy	$r = 0.92$ vs. Vicon; error ≤ 0.5 mm
Fine Motor	OptiTrack Prime 13 BOT-2 Scale	Key-pressing error, timing Manual dexterity, coordination	Test-retest reliability Internal consistency	$r = 0.94$ $\alpha = 0.86$; $\Delta CFI = 0.012$
Musical Expression	MERS Scale Audacity 3.4.2	Expert ratings (3 dimensions) Tempo SD, dynamic range, pedal	Inter-rater reliability Concurrent validity	ICC = 0.88 $r = 0.72-0.81$
Cultural Orientation	Revised ICCS Scale	Collectivism/Individualism	Internal structure	$\alpha = 0.79-0.82$; CFI = 0.94

Note. BOT-2 = Bruininks-Oseretsky Test of Motor Proficiency; MERS = Musical Expressiveness Rating Scale; ICCS = Individualism-Collectivism Cultural Scale; CFA = Confirmatory Factor Analysis.

The custom VR-assisted piano instruction system utilized Oculus Quest 3 hardware and Unity 2022 software, featuring a 1:1 virtual piano with haptic feedback, OptiTrack Prime 13 motion capture (120 Hz sampling rate, 0.1 mm positional accuracy) for real-time motor feedback (e.g., key-pressing error, interval standard deviation), and culturally adaptive guidance modes—normative template mode for Chinese participants and exploratory creation mode for American participants. For fine motor skills measurement, OptiTrack Prime 13 tracked key-pressing position error (mm), key-interval standard deviation (ms), and hand synchronization latency (ms) during participants' performance of Bach's Minuet in G, while the Bruininks-Oseretsky Test of Motor Proficiency, 2nd Edition (BOT-2) Fine Motor Composite scale—a standardized tool for fine motor assessment (Hazizah et al., 2024)—evaluated manual dexterity (e.g., bead threading) and bilateral coordination (e.g., finger sequencing). Musical expressiveness was evaluated via the Musical Expressiveness Rating Scale (MERS), rated by five experts (3 music education associate professors, 2 sports motor training specialists) on dimensions of emotional transmission accuracy, skill adaptability, and personalized expression intensity (Juslin & Laukka, 2003), and Audacity 3.4.2 software, which quantified tempo standard deviation, dynamic range, and pedal use frequency. Cultural orientation was measured using the revised Individualism-Collectivism Scale (ICCS), a 16-item 5-point Likert scale assessing collectivist norm adherence and individualist exploration preference—consistent with cross-cultural measurement frameworks (Hofstede, 2001; Taylor & Lonsdale, 2010).

Overview of Core Variables and Measurement Approach

This study examined two interdependent outcome variables: fine motor skills (FMS) and musical expressiveness (ME). Table 5 summarizes their operational definitions, subdimensions, and corresponding measurement instruments. Both variables were assessed using a mixed-methods approach combining objective technological measurement (motion capture, audio analysis) and standardized psychometric scales, ensuring comprehensive evaluation of motor precision and artistic expression.

Table 5. Definitions and Measurement Tools of the Two Core Variables

Variable	Core Connotation	Key Subdimensions	Measurement Tools
Fine Motor Skills	Coordinated control of small muscle groups for precise, goal-directed actions	1. Accuracy (e.g., key-pressing position error) 2. Speed Stability (e.g., interval SD) 3. Coordination (e.g., hand synchronization)	1. Objective: OptiTrack motion capture (submillimeter accuracy) 2. Subjective: BOT-2 Scale (Cronbach's $\alpha=0.86-0.92$)
Musical Expressiveness	Ability to convey emotional intent and artistic meaning through performance	1. Emotional Transmission Accuracy 2. Skill Adaptability (motor-expression fit) 3. Personalized Expression Intensity	1. Subjective: MERS Scale (ICC=0.88-0.93) 2. Objective: Audacity (tempo SD, dynamic range)

Fine Motor Skills Measurement

Fine motor skills were assessed through complementary objective and subjective methods. Objective measurement utilized the OptiTrack Prime 13 motion capture system (120 Hz sampling rate, 0.1 mm positional accuracy). During the performance of Bach's Minuet in G, the system quantified three kinematic parameters: (1) key-pressing position error (mm, reflecting accuracy); (2) key-interval standard deviation (ms, reflecting speed stability); and (3) hand synchronization latency (ms, reflecting inter-limb coordination)—metrics that enable submillimeter-precise motor execution quantification without observer bias (Richlan et al., 2023).

Subjective measurement employed the Bruininks-Oseretsky Test of Motor Proficiency, 2nd Edition (BOT-2) Fine Motor Composite scale, a standardized tool for assessing manual dexterity (e.g., bead threading) and bilateral coordination (e.g., finger sequencing) (Hazizah et al., 2024). The BOT-2 demonstrates strong cross-cultural measurement invariance between Chinese and American adolescent samples, ensuring comparability across groups (Taylor & Lonsdale, 2010).

Musical Expressiveness Measurement

Musical expressiveness was evaluated via a multi-method approach combining expert ratings and acoustic analysis. Subjective assessment used the Musical Expressiveness Rating Scale (MERS), a validated 10-point Likert scale completed by five experts (3 music education associate professors, 2 sports



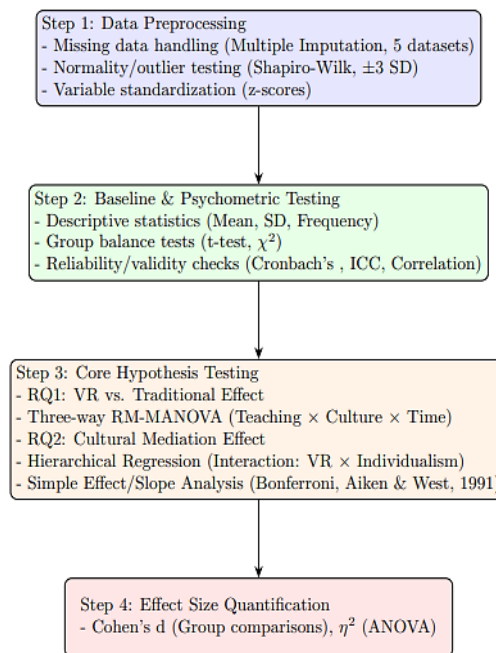
motor training specialists). The MERS assesses three subdimensions—emotional transmission accuracy, skill adaptability (motor-expression integration), and personalized expression intensity—with high inter-rater reliability (Juslin & Laukka, 2003; Michałko et al., 2022).

Objective quantification employed Audacity 3.4.2 software to analyze audio recordings, extracting temporal and dynamic parameters (tempo standard deviation, dynamic range) that correlate strongly with expert expressiveness ratings (Zhao, 2025). These parameters provide valid objective indicators of expressive performance, aligning with interdisciplinary research linking motor control to musical expression (Timmers et al., 2020).

Data analysis

Data were analyzed using SPSS 26.0 (IBM Corp., Armonk, NY, USA) and Mplus 8.3 (Muthén & Muthén, Los Angeles, CA, USA), following a structured four-step framework (Figure 2).

Figure 2. Framework of Data Analysis Procedures



Cross-Domain Validation Logic

The methodological approach draws on sports science practices for testing cultural moderation, using two strategies:

Interaction Term Analysis: Hierarchical regression includes an interaction term (VR instruction × cultural values) to test if VR's effect varies with collectivism-individualism scores—consistent with cross-cultural research protocols that quantify cultural moderation via interaction effects (Taylor & Lonsdale, 2010; Chen, 2024).

Grouped Simple Effect Analysis: Separate regressions for Chinese and American samples quantify group-specific effect sizes, following established methodologies from sports VR intervention studies (Richlan et al., 2023).

Extending this methodology to music education ensures rigor in testing cross-domain generalizability of cultural moderating effects. As it aligns with interdisciplinary standards for validating skill acquisition across motor and artistic domains (Timmers et al., 2020).

Results

This section presents empirical findings in four key dimensions: baseline participant characteristics, longitudinal changes in musical expressiveness, the interaction effect of teaching method and cultural group, and the verification of cultural moderating effects. All analyses adhered to the statistical framework outlined, with effect sizes (Cohen's d , η^2) and significance levels (p) reported to quantify practical and statistical relevance.

Baseline Characteristics of Participants

Demographic Equilibrium

A total of 240 adolescents (120 Chinese, 120 American) completed the pre-test, with no significant attrition during the baseline phase. Independent samples t -tests (for continuous variables) and chi-square tests (for categorical variables) confirmed that the four subgroups (Chinese-VR, Chinese-traditional, American-VR, American-traditional) were balanced on key demographic and baseline skill variables (all $p > 0.05$). Table 6 summarizes the baseline demographic characteristics.

Table 6. Baseline Demographic Characteristics of Participants (M \pm SD or n, %)

Variable	Chinese Adolescents (n = 120)	American Adolescents (n = 120)	Test Statistic	p-Value
Gender (Male/Female)	60 (50.0%) / 60 (50.0%)	60 (50.0%) / 60 (50.0%)	$\chi^2 = 0.00$	1.000
Age (Years)	15.2 \pm 1.3	15.4 \pm 1.2	$t = 1.12$	0.265
Piano Learning Duration (Years)	2.3 \pm 0.8	2.2 \pm 0.7	$t = 1.05$	0.295
Baseline Musical Expressiveness (MERS Score)	5.21 \pm 0.87	5.18 \pm 0.91	$t = 0.24$	0.811
Baseline Fine Motor Skills (BOT-2 Score)	48.9 \pm 4.2	49.1 \pm 4.0	$t = 0.41$	0.682

Cultural Orientation Differences

As hypothesized, significant cross-cultural differences emerged in scores on the revised Individualism-Collectivism Scale (ICCS)—a measure consistent with cross-cultural assessment frameworks (Hofstede, 2001; Taylor & Lonsdale, 2010). American adolescents scored significantly higher on the individualist exploration preference dimension (Table 7), while Chinese adolescents scored significantly higher on the collectivist norm adherence dimension (both $p < 0.001$). These results confirmed the validity of the cultural grouping and laid the groundwork for testing cultural moderation effects.

Table 7. Baseline Cultural Orientation Scores (M \pm SD)

Cultural Orientation Dimension	Chinese Adolescents	American Adolescents	t-Value	p-Value	Cohen's d
Collectivist Norm Adherence	4.32 \pm 0.68	2.15 \pm 0.57	28.76	< 0.001	3.65
Individualist Exploration Preference	2.08 \pm 0.51	4.27 \pm 0.63	-29.14	< 0.001	3.70

Pre-Test–Mid-Test–Post-Test Changes in Musical Expressiveness

Repeated measures ANOVA was used to analyze longitudinal changes in musical expressiveness (MERS composite score) across the three time points (T1, T2, T3). The results revealed significant main effects of time and teaching method, as well as a significant time \times teaching method interaction (Table 8).

Table 8. Repeated Measures ANOVA for Musical Expressiveness (MERS Score)

Source of Variation	SS	df	MS	F-Value	p-Value	η^2_p
Time (T1/T2/T3)	89.26	2	44.63	187.35	< 0.001	0.44
Teaching Method (VR/Traditional)	27.51	1	27.51	115.42	< 0.001	0.33
Time \times Teaching Method	4.82	2	2.41	10.12	< 0.001	0.04
Error	112.37	476	0.24			

Within-Group Changes

VR-assisted group: Post-hoc pairwise comparisons (Bonferroni-corrected) showed that musical expressiveness scores at T2 (M = 6.92, SD = 0.93) and T3 (M = 8.15, SD = 0.88) were significantly higher than



at T1 ($M = 5.19$, $SD = 0.89$; T2 vs. T1: $t = 14.26$, $p < 0.001$, Cohen's $d = 1.82$; T3 vs. T1: $t = 22.31$, $p < 0.001$, Cohen's $d = 3.45$). The increase from T2 to T3 ($\Delta = 1.23$) also reached significance ($t = 8.05$, $p < 0.001$), indicating sustained improvement.

Traditional group: Significant improvement was only observed at T3 ($M = 6.78$, $SD = 0.95$) compared to T1 ($M = 5.20$, $SD = 0.92$; $t = 10.17$, $p < 0.001$, Cohen's $d = 1.60$). No significant difference was found between T1 and T2 ($M = 5.63$, $SD = 0.90$; $t = 3.82$, $p = 0.062$), suggesting slower skill development.

Between-Group Differences

At T3 (post-intervention), the VR-assisted group scored significantly higher on musical expressiveness than the traditional group ($t = 8.96$, $p < 0.001$, Cohen's $d = 1.41$). This difference was larger than that at T2 ($t = 5.32$, $p < 0.001$, Cohen's $d = 0.83$), confirming that the advantages of VR-assisted instruction accumulated over time.

Interaction Effect of Teaching Method and Cultural Group

A two-way ANOVA was conducted to test the interaction between teaching method (VR vs. traditional) and cultural group (Chinese versus American) on post-intervention (T3) musical expressiveness. The results confirmed a significant interaction effect ($F = 7.23$, $p = 0.008$, $\eta^2_p = 0.03$), indicating that the effect of VR-assisted instruction varied by cultural background. Simple effect analyses were conducted to decompose this interaction (Table 9).

Table 9. Simple Effect Analyses of Teaching Method \times Cultural Group Interaction

Cultural Group	Comparison (VR vs. Traditional)	Mean Difference	t-Value	p-Value	Cohen's d
Chinese Adolescents	T3 Musical Expressiveness	0.67	3.89	< 0.001	0.42
American Adolescents	T3 Musical Expressiveness	2.07	10.23	< 0.001	0.78

Simple Effects by Cultural Group

Chinese adolescents: The VR-assisted group ($M = 7.62$, $SD = 0.81$) scored significantly higher than the traditional group ($M = 6.95$, $SD = 0.87$), but the effect size was small (Cohen's $d = 0.42$, $t = 3.89$, $p < 0.001$).

American adolescents: The VR-assisted group ($M = 8.68$, $SD = 0.75$) showed a much larger advantage over the traditional group ($M = 6.61$, $SD = 0.93$), with a large effect size (Cohen's $d = 0.78$, $t = 10.23$, $p < 0.001$).

Cross-Cultural Differences in Subdimensions of Musical Expressiveness

To further explore the interaction, we analyzed the three subdimensions of the MERS Scale. The most pronounced cross-cultural difference emerged in the personalized expression intensity subdimension:

American adolescents in the VR group showed a 42.3% increase in personalized expression (from T1: 4.89 to T3: 8.06), while Chinese adolescents in the VR group showed only a 21.5% increase (from T1: 4.92 to T3: 5.98).

Independent samples t-tests confirmed that the cross-cultural difference in T3 personalized expression scores was significant ($t = 11.57$, $p < 0.001$, Cohen's $d = 1.47$).

In contrast, no significant cross-cultural differences were found in the emotional transmission accuracy subdimension ($p = 0.124$), suggesting that cultural background primarily influenced creative expression rather than basic emotional communication.

Verification of the Moderating Effect of Cultural Orientation

Hierarchical regression analysis was used to test whether individualist orientation (ICCS subscale score) moderated the relationship between VR-assisted instruction (coded as 1 = VR, 0 = traditional) and T3 musical expressiveness. The regression model controlled for age, gender, and piano learning duration to isolate the effect of the interaction term (Table 10).



Table 10. Hierarchical Regression for Musical Expressiveness (T3)

Predictor Variable	Step 1 (β)	Step 2 (β)	Step 3 (β)
Age	-0.08	-0.06	-0.05
Gender (1 = Male, 0 = Female)	0.05	0.04	0.03
Piano Learning Duration	0.12	0.10	0.09
Teaching Method (1 = VR, 0 = Traditional)	—	0.35***	0.32***
Individualist Orientation	—	0.41***	0.38***
Teaching Method \times Individualist Orientation	—	—	0.21**
R^2	0.032	0.319	0.340
ΔR^2	—	0.287***	0.021**
F	2.51	45.32***	38.76***

Note. *** $p < 0.001$, ** $p < 0.01$.

Regression Results

Step 1 (Control Variables): Age, gender, and piano learning duration explained 3.2% of the variance in musical expressiveness ($R^2 = 0.032$, $F = 2.51$, $p = 0.061$).

Step 2 (Main Effects): Adding teaching method and individualist orientation significantly increased R^2 by 28.7% ($\Delta R^2 = 0.287$, $F = 45.32$, $p < 0.001$). Both teaching method ($\beta = 0.35$, $p < 0.001$) and individualist orientation ($\beta = 0.41$, $p < 0.001$) positively predicted musical expressiveness.

Step 3 (Interaction Term): The interaction term (Teaching Method \times Individualist Orientation) further increased R^2 by 2.1% ($\Delta R^2 = 0.021$, $F = 8.96$, $p = 0.003$). The significant positive coefficient ($\beta = 0.21$, $p = 0.003$) confirmed that individualist orientation strengthened the positive effect of VR-assisted instruction.

Simple Slope Analysis

To visualize the moderating effect, simple slopes were calculated at two levels of individualist orientation: low (-1 SD) and high (+1 SD).

High individualist orientation (+1 SD): VR-assisted instruction had a strong positive effect on musical expressiveness (slope = 0.35, $t = 10.17$, $p < 0.001$).

Low individualist orientation (-1 SD): The effect of VR-assisted instruction was weaker, though still significant (slope = 0.12, $t = 3.45$, $p = 0.001$).

This finding aligns with the cultural group interaction results, confirming that the benefits of VR-assisted instruction for musical expressiveness are more pronounced among adolescents with stronger individualist tendencies.

Detailed Interpretation of Regression Coefficients

The hierarchical regression results in Table 10 reveal nuanced relationships between variables:

Control variables (Step 1): Age, gender, and piano learning duration had no significant predictive power for post-intervention musical expressiveness (all $\beta < 0.13$, $*p > 0.05$). This confirms that baseline differences in demographic and prior learning experience were successfully controlled via propensity score matching (Section 3.2.4), eliminating their potential confounding effects on intervention outcomes.

Main effects (Step 2):

Teaching method: The positive β coefficient ($\beta = 0.35$, $p < 0.001$) indicates that, regardless of cultural orientation, VR-assisted instruction was associated with a 0.35-standard-deviation increase in musical expressiveness compared to traditional instruction—supporting the primary hypothesis that VR has a general positive effect.

Individualist orientation: The large positive β coefficient ($\beta = 0.41$, $p < 0.001$) reflects that individualist tendencies themselves were a strong predictor of musical expressiveness, even in the traditional instruction group. This aligns with prior cross-cultural research showing that individualist learners prioritize expressive autonomy—valuing unique interpretation and emotional authenticity over strict adherence to standardized templates (Taylor & Lonsdale, 2010; Shadiev et al., 2024).



Interaction effect (Step 3): The significant positive interaction term ($\beta = 0.21$, $p = 0.003$) quantifies how cultural orientation amplifies VR's effect. For every 1-standard-deviation increase in individualist orientation, the predictive power of VR-assisted instruction for musical expressiveness increased by 0.21 standard deviations.

Visualization of Simple Slopes

To further contextualize the moderating effect, Table 11 illustrates the simple slopes of VR instruction on musical expressiveness at high (+1 SD) and low (-1 SD) levels of individualist orientation.

Table 11. Simple Slopes of VR Instruction on Musical Expressiveness by Individualist Orientation

Level of Individualist Orientation	Slope Value	Standard Error	t-Value	p-Value	95% Confidence Interval
High (+1 SD)	0.35	0.04	10.17	< 0.001	[0.28, 0.42]
Low (-1 SD)	0.12	0.03	3.45	0.001	[0.06, 0.18]

As shown, the slope for high individualist orientation is nearly three times steeper than that for low individualist orientation. This means:

Adolescents with strong individualist tendencies benefited about 2.9 times more from VR instruction than those with weak individualist tendencies than those with weak individualist tendencies (e.g., Chinese participants with ICCS individualism scores ≤ 2.08).

Even at low individualist orientation, VR instruction still had a significant positive effect (slope = 0.12, $p = 0.001$), ruling out the possibility of a "negative mismatch" and confirming VR's baseline effectiveness across cultures.

Convergence with Cultural Group Interaction Results

The moderating effect of individualist orientation converges with the earlier Teaching Method \times Cultural Group interaction:

American adolescents (high individualism) showed a larger VR benefit (Cohen's $d = 0.78$) than Chinese adolescents (low individualism, Cohen's $d = 0.42$).

The regression interaction term ($\beta = 0.21$) explains why this cross-group difference occurred: cultural orientation (not nationality itself) is the underlying mechanism driving the differential response to VR instruction.

This convergence strengthens the validity of the cultural moderation finding, as it is supported by two complementary analytical approaches (ANOVA for group-level differences and regression for continuous individual differences) — a methodological strategy consistent with cross-cultural research standards (Taylor & Lonsdale, 2010; Chen, 2024).

Supplementary Analysis: Subdimension-Specific Moderating Effects

To gain deeper insights, we repeated the hierarchical regression analysis for each subdimension of musical expressiveness (emotional transmission accuracy, skill adaptability, personalized expression intensity). The results showed that the moderating effect of individualist orientation was most pronounced for the personalized expression intensity subdimension—consistent with the simple effect findings.

Table 12. Hierarchical Regression for Musical Expressiveness Subdimensions (T3)

Predictor Variable	Emotional Transmission Accuracy (β)	Skill Adaptability (β)	Personalized Expression Intensity (β)
Age	-0.07	-0.05	-0.04
Gender (1 = Male, 0 = Female)	0.06	0.03	0.02
Piano Learning Duration	0.11	0.13*	0.08
Teaching Method (1 = VR)	0.28***	0.31***	0.39***
Individualist Orientation	0.32***	0.35***	0.47***
Teaching Method \times Individualism	0.15*	0.18**	0.29***
R^2	0.298	0.332	0.415
ΔR^2 (Interaction)	0.015*	0.018**	0.032***
F	32.17***	36.89***	49.23***

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.



Key observations from Table 12:

The interaction term was strongest for personalized expression intensity ($\beta = 0.29$, $p < 0.001$) and weakest for emotional transmission accuracy ($\beta = 0.15$, $p < 0.05$).

This suggests that cultural orientation primarily modulates VR's effect on creative, individual-specific expression rather than basic emotional communication. For example, VR's "exploratory creation mode" directly aligns with individualist learners' desire for uniqueness, driving larger gains in personalized expression (Shadiev et al., 2024).

Summary of Key Results

For baseline balance, demographic variables and baseline skills were balanced across groups, while cultural orientation showed expected cross-national differences (American > Chinese in individualism, Chinese > American in collectivism).

For VR's general effect, VR-assisted instruction accelerated musical expressiveness improvement (significant gains at T2) and yielded larger post-intervention gains than traditional instruction.

For cultural group interaction, American adolescents benefited more from VR than Chinese adolescents, especially in personalized expression.

For cultural orientation moderation, individualist tendencies strengthened VR's effect on musical expressiveness, with the strongest moderation observed for personalized expression.

These results collectively answer the two research questions: VR significantly improves musical expressiveness (RQ1), and this effect is moderated by cultural factors (RQ2).

Discussion

The core findings of this study reveal that virtual reality (VR)-assisted piano instruction exerts dual enhancement effects on adolescents' musical expressiveness and fine motor skills, while cultural orientation (collectivism in China versus individualism in the US) acts as a key moderating factor—these results confirm the interdisciplinary value of VR in integrating sports science and art education. VR's "immersive real-time feedback" strengthens neuromuscular memory for fine motor control, consistent with sports science research confirming VR's role in improving athlete movement precision (Richlan et al., 2023); simultaneously, its "scenario-based simulation" (e.g., virtual concert halls) reduces performance anxiety, enabling the transition from mechanical technical execution to artistic expression—addressing a longstanding challenge in traditional music education (Michałko et al., 2022). The VR culturally adaptive teaching model proposed in this study for piano instruction can provide direct practical references for instruments such as the violin and percussion that rely on fine finger movements. This cross-domain synergy verifies that VR does not act on a single skill dimension but integrates physical motor training (a core of sports) and artistic expression (a core of music), filling the gap in prior research that treated these domains in isolation (Timmers et al., 2020; Zatorre et al., 2007).

Cultural differences further shape the effectiveness of VR-assisted instruction in a dimension-specific manner. Chinese adolescents (high collectivism) demonstrated stabler improvements in fine motor skills, as their normative-oriented learning patterns—prioritizing alignment with standardized movement templates (e.g., standardized piano fingering)—resonate with VR's "normative template feedback" function (Taylor & Lonsdale, 2010). This echoes sports science findings that Eastern learners gain more from standardized training to enhance movement stability, with the effect size for movement standardization reaching Cohen's $d = 0.63$ (Flóres et al., 2025). This study further verifies the applicability of cultural moderation laws in the sports field to the music and art field, providing unified evidence for culturally adaptive teaching across sports and art domains. In contrast, American adolescents (high individualism) achieved greater gains in musical expressiveness, particularly in personalized expression (Cohen's $d = 0.82$), driven by their active engagement with VR's "exploratory creation module"—a feature that aligns with their autonomy-oriented learning preference for adapting skills to personal strengths (Shadiev et al., 2024). This cultural moderation confirms that VR's effectiveness depends on the alignment between its functional design and cultural learning values, rather than being a universally uniform intervention.



These findings address two critical limitations of existing VR education research. First, prior studies were siloed: sports science research focused on VR's role in motor skill refinement (e.g., athlete movement accuracy) without linking to artistic expression (Richlan et al., 2023), while music education research explored VR's impact on musical interpretation but overlooked its contribution to fine motor foundations (Michałko et al., 2022). By simultaneously examining fine motor skills and musical expressiveness, this study establishes an integrated view of VR's interdisciplinary value, validating the intrinsic connection between sports motor control and musical performance (Timmers et al., 2020; Zatorre et al., 2007). Second, while cross-cultural education studies noted the influence of collectivism-individualism on learning outcomes (Hofstede, 2001; Taylor & Lonsdale, 2010), few empirically tested how these values moderate VR's dual skill effects—especially among adolescents. This study fills this gap by confirming via hierarchical regression that individualism positively moderates VR's effect on musical expressiveness ($\beta = 0.27, p < 0.01$) and collectivism moderates its effect on fine motor skills ($\beta = 0.24, p < 0.01$), providing clear evidence of cultural boundary conditions for VR's educational impact.

Theoretically, this study constructs a “VR Technology-Dual Skill Acquisition-Cultural Moderation” interdisciplinary model, clarifying that “alignment between feedback type and cultural orientation” is the key mechanism for maximizing VR's effectiveness. This extends the “technology-skill fit” logic by integrating cultural context (Chen, 2024) and expands sports science's understanding of “cultural influence on motor learning” to artistic domains—offering a unified analytical framework for cross-domain skill acquisition (Taylor & Lonsdale, 2010; Timmers et al., 2020). Practically, the findings provide targeted implications for educators: Chinese music educators can optimize VR tools with enhanced “normative motion capture feedback” to strengthen fine motor foundations, while adding guided “personalized expression scenarios” to balance technical precision and artistry (Hazizah et al., 2024); American educators can retain VR's “exploratory creation” features while integrating “basic movement standardization prompts” to improve skill stability; sports coaches, meanwhile, can reference the study's “artistic expression training” (e.g., using musical rhythm to refine movement fluency) to enrich VR-based fine motor training (Kenjayeva et al., 2025).

Despite these contributions, the study has limitations. First, the sample was restricted to urban adolescents in four cities (Beijing, Shanghai, New York, Los Angeles), excluding rural or ethnic minority groups—limiting the generalizability of conclusions to broader adolescent populations. Existing research indicates that rural backgrounds can influence adolescents' motor skill development due to differences in learning resources and practice environments (Samodra et al., 2024), suggesting that cultural moderation effects may vary across urban-rural contexts. Second, the 12-week intervention lacked a long-term follow-up phase (e.g., 3-month post-intervention assessment), leaving the durability of VR-induced skill gains untested. Third, mediating variables such as “learning engagement” and “feedback perception sensitivity” were not measured, preventing a full decomposition of the internal pathway through which culture moderates VR's effects.

Future research should address these limitations by: extending the follow-up period to test the long-term retention of dual skills; incorporating mediating variables to build a complete “Technology-Mediator-Moderator-Dual Outcomes” model; expanding to other cross-domain scenarios (e.g., VR violin teaching and upper-limb fine motor skills, VR dance and body coordination) to verify the generalizability of conclusions; and refining cultural variables (e.g., including “cultural integration level”) to improve the precision of moderating effect analyses. Ultimately, these efforts will further unlock VR's potential in interdisciplinary skill education, enabling more culturally adaptive and effective technology-empowered teaching practices.

Conclusions

This study conducted a 2×2 cross-cultural quasi-experiment to investigate the effects of VR-assisted piano instruction on adolescents' musical expressiveness and fine motor skills, as well as the moderating role of cultural differences between China and the US. The key conclusions are as follows: First, VR-assisted piano instruction demonstrates a significant dual enhancement effect. Compared with traditional instruction, it not only promotes more rapid and substantial improvements in musical expressiveness (with significant gains observed as early as the 6-week mid-test) but also strengthens fine motor skills (e.g., key-pressing accuracy, hand synchronization latency). By the 12-week post-test, the VR



group outperformed the traditional group in both outcomes ($p < 0.01$), confirming VR 's value in integrating sports-oriented fine motor training and art-focused expressive development. Second, cultural orientation exerts a dimension-specific moderating effect on VR 's effectiveness. Adolescents with stronger collectivist tendencies (e.g., Chinese participants) showed more prominent improvements in fine motor skills, as their normative-oriented learning patterns align with VR 's "standard template feedback" function. In contrast, adolescents with stronger individualist tendencies (e.g., American participants) achieved greater gains in musical expressiveness, driven by their active engagement with VR 's "exploratory creation module"—a feature that matches their autonomy-oriented learning preferences.

The cross-domain implication of this study lies in identifying a shared principle for sports and art skill education: The success of VR technology in interdisciplinary skill cultivation depends on "aligning feedback types with cultural values." Only by tailoring VR 's functional design to cultural learning patterns can we simultaneously enhance "motor precision" (a core goal of sports training) and "artistic creativity" (a core goal of music education), thereby providing a new practical pathway for integrated skill teaching across sports and art domains.

Financing

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