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The Impact of Industry Revolution 4.0 Technologies and Education 4.0 on PE Learning Outcomes among University Students in Heilongjiang, China

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Abstract: Digital transformation, driven by Industry Revolution 4.0 (IR 4.0) and Education 4.0 (Ed 4.0), is significantly reshaping education, particularly practical subjects like Physical Education (PE). A study investigating this impact on PE learning outcomes among 449 university students in Heilongjiang, China, utilized a quantitative cross-sectional design with Structural Equation Modeling (SEM). The research examined the relationships between five key technological factors Virtual Reality (VR), Augmented Reality (AR), Internet of Things (IoT), Big Data analytics, and Cloud Computing and PE learning outcomes. All constructs demonstrated high reliability (Cronbach's alpha > 0.90). The findings revealed remarkably strong positive relationships between all technological factors and PE learning outcomes. Cloud Computing exhibited the strongest impact ($\beta = 0.996$, $p < .001$), followed by IoT ($\beta = 0.946$, $p < .001$), Big Data ($\beta = 0.937$, $p < .001$), AR ($\beta = 0.935$, $p < .001$), and VR ($\beta = 0.934$, $p < .001$). Strong intercorrelations among these factors suggest synergistic benefits when implemented together. This study confirms that comprehensive digital transformation strategies employing multiple complementary technologies are more effective than isolated approaches, offering evidence-based guidance for institutions and policymakers to invest in robust technological infrastructure, especially cloud computing, to enhance PE education.

Keywords: Industry revolution 4.0, education 4.0, physical education, digital transformation, educational technology

1. Introduction

Exercise can improve a person's abilities, well-being, and physical fitness (Ahmad et al., 2024). There is growing interest in how IR 4.0 and rapidly developing educational technologies, especially those applied in PE instruction, can improve the learning process (Bujang et al., 2020). The Internet of Things (IoT), Cyber-physical Systems (CS), Artificial Intelligence (AI) and Data Analytics (DA) are components of IR 4.0, the fourth industrial revolution that has had a significant impact on many industries (Benavides et al., 2020). In the context of higher education, Education 4.0 (Ed 4.0) has aligned these emerging innovations with traditional teaching methods to create integrated digital learning environments.

The integration of IR 4.0 technologies with Ed 4.0 approaches can provide students with engaging learning experiences and transform PE instruction. These technologies can enhance teaching effectiveness through personalized education, real-time monitoring and feedback, and support for data-driven decision-making (Butt et al., 2020). Such integration has the potential to improve PE learning outcomes, performance assessment methods, and skill development processes. However, despite these potential advantages, research examining the specific impacts, limitations, and practical implementation approaches of integrating IR 4.0 with Ed 4.0 in China's PE system remains limited.

Therefore, this study aims to investigate the integration of IR 4.0 and Ed 4.0 technologies in China's physical education system, specifically examining their impacts on teaching effectiveness, student engagement, and learning outcomes. By addressing this research gap, the study contributed to understanding how these emerging technologies can be practically implemented in Chinese PE contexts, providing evidence-based insights for educators and policymakers. The significance of this research lies in its potential to inform the development of technology-enhanced PE curricula that

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can improve student physical literacy, motivation, and overall educational experience in the Chinese higher education context.

With the rapid development of digital technology and the transformation of traditional industrial processes, the emergence of IR 4.0 represents society's response to urgent technological needs. The concept of IR 4.0 was first formally introduced at the 2011 Hannover Messe in Germany, which has become the world's largest industrial exposition. This event highlighted how Data Analytics (DA), Internet of Things (IoT), Artificial Intelligence (AI) and Cyber-physical Systems (CS) have become the foundational technologies driving the Fourth Industrial Revolution (Chanthiran et al., 2022).

Industrial revolutions evolve with changing times and changing demands of society. The first revolution mechanized water and steam power, and the second revolution utilized electricity and assembly lines for mass production. The third revolution promoted automated production. IR 4.0 brings a new era of industrial technology. Systems within IR 4.0 incorporate cutting-edge technologies, highlighting the importance of technical support, openness, interoperability, and the decentralization of decision-making processes. Parallel to industrial transformation, Education 4.0 (Ed 4.0) has emerged as the educational paradigm that aligns with the digital age. The development of IR 4.0 and Ed 4.0 has changed the educational environment, offering solutions to the problems of standardization, non-personalization, and low quality of traditional education methods. Ed 4.0 and IR 4.0 merge digital capabilities to encourage innovation, critical thinking, problem-solving, teamwork and computer skills abilities that students need in a world where global technology and culture are rapidly evolving.

1.1 Research Gap and Significance

Ed 4.0 and IR 4.0 are integrated with PE but are poorly researched. To enhance technology integration and expand our understanding of China, we need to identify these research gaps and opportunities (Cojocaru et al., 2022). There is also a lack of research in the field of PE. Most studies have focused on different types of PE programs. Football, basketball and swimming need to study IR 4.0. (Ahmad et al., 2024). Each PE comes with different challenges and opportunities, so strategies can be adapted to suit different PE environments (Costa et al., 2022). More research is needed on age groups integrating technology. Focus primarily on K-12 or higher education. In primary and pre-school education, IR 4.0 technologies should be used in PE. Understanding developmental and age-appropriate teaching methods can help develop technology-integrated treatments for different age groups.

Research on PE in IR 4.0 is equally important. Using integrated technology can improve learning, but innovative teaching methods are still needed. VR, DA and gamification, project-based learning or collaborative problem-solving in PE classes, wearable technology, etc. can increase student engagement and learning effectiveness (Bujang et al., 2020). Further investigation is needed into the ethical and social implications of integrating technology into traditional classroom instruction. Concerns have arisen about social interactions, physical activity, data security, and privacy. Long-term research on the impact of technology integration in PE on academic performance, skill development, and health would also be beneficial.

Mixed methods in PE are explained using quantitative and qualitative data collection methods on the complex dynamics of IR 4.0 and integration of Ed 4.0 and IR 4.0 technologies (Benavides et al., 2020). Comparative analyses, longitudinal surveys across educational settings, and experimental methods increase the generalizability and validity of the study. In order to better understand how IR 4.0 and Ed 4.0 are integrated with PE, it is necessary to overcome these differences and look for possible methods for future research. By using this data, evidence-based strategies, policies, and interventions can be developed to improve student engagement, skill development, and physical learning.

1.1 Research Objectives

a. To determine the impact of VR on PE learning outcomes among students in Heilongjiang, China.
b. To determine the impact of AR on PE learning outcomes among students in Heilongjiang, China.
c. To determine the IoT effect on PE learning outcomes among students in Heilongjiang, China.
d. To determine Big Data effect on PE learning outcomes among students in Heilongjiang, China.
e. To determine Cloud Computing effect on PE learning outcomes among students in Heilongjiang, China.

1.2 Research Question

a. Is there any significant difference on the impact of VR on PE learning outcomes among students in Heilongjiang, China?
b. Is there any significant difference in the impact of AR on PE learning outcomes among students in Heilongjiang, China?
c. Is there any significant difference in the IoT effect on PE learning outcomes among students in Heilongjiang, China?
d. Is there any significant difference on Big Data effect on PE learning outcomes among students in Heilongjiang, China?
e. Is there any significant difference in Cloud Computing effect on PE learning outcomes among students in Heilongjiang, China?

f. Among VR、AR、IOT、Big Data、Cloud Computing, which factor is a prediction for PE learning outcomes among students in Heilongjiang, China?

2. Literature Review

2.1 The Relationship between VR and Learning outcomes in Learning PE

Some scholars use three characteristics to describe VR: telepresence, interactivity and immersion. (Vonitsanos et al., 2024). Telepresence is the feeling of being outside one's actual location. Interactivity refers to the extent to which users can change and influence their virtual environment in real-time. Experts agree on the concepts of interactivity and presence, but immersion is different (Chanthiran et al., 2022). Some scholars believe that immersion can be defined as an objective measure of technical capabilities. The comprehensive framework for evaluating virtual environments. These include factors like inclusiveness, which measures the degree to which actual reality is omitted in favor of a virtual one. Extensiveness is also crucial, referring to how many sensory modalities are engaged within the environment. Another aspect is the scope of the field of view that a user perceives. Additionally, the richness, resolution, or overall quality of the visual displays are pivotal in creating a convincing virtual space. Finally, the consistency between proprioceptive feedback our sense of body position and movement and the corresponding visual information is essential for a seamless and immersive experience. These elements collectively contribute to the integrity and believability of a virtual environment, impacting the user's experience and interaction within the virtual world. On the other hand, other researchers define immersion as a subjective engagement that can take many forms, including cognitive immersion, emotional immersion and spatial immersion.

Teaching styles were proposed more than 50 years ago (Butt et al., 2020). However, many educators still regard it as the primary method of teaching (Ahmad et al., 2024). In the 1970s, some new teaching frameworks continued to emerge, such as curriculum models, teaching models and educational models (Benavides et al., 2020). At the core of model-based instruction is the shift of focus from the responsibilities of teachers and subjects to the needs of students (Butt et al., 2020).

The greatest contribution of the educational model is the emphasis on students and their individuality, and the special attention given to the educational context in which practice takes place. Some models have recently received more attention from researchers than others due to their widespread use and review by researchers in a variety of educational contexts (Bujang et al., 2020). Models such as cooperative learning are relatively late in the field of PE and appeared earlier in other subjects such as science, mathematics, and English. On the other hand, models such as "comprehensive teaching games" and "PE" have become hot spots in PE subject research. Scientific research based on different backgrounds and contents (Cojocaru et al., 2022).

At the beginning of the new century, the assessment of cooperative learning was linked to the paradigm of peer-assisted learning (Chanthiran et al., 2022). This paradigm ignores the specific consequences of cooperative learning implementation and instead focuses on peer feedback. Since then, many papers have investigated its use in PE, extending the scope of research to physical, emotional, social and cognitive aspects (González-Pérez & Ramírez-Montoya, 2022). The papers that investigated the use of cooperative learning in PE, extending the scope of research to physical, emotional, social and cognitive aspects, likely reached several important conclusions. In terms of physical aspects, cooperative learning can enhance motor skill development, physical fitness, and overall performance in PE by providing opportunities for students to practice, observe, and receive feedback from their peers (Vonitsanos et al., 2024). Emotionally, engaging in cooperative learning activities can promote positive emotions, such as enjoyment, satisfaction, and a sense of belonging among students. It may also reduce anxiety and fear of failure by creating a supportive learning environment (Chanthiran et al., 2022). From a social perspective, cooperative learning fosters social skills development, including communication, leadership, trust-building, and conflict resolution. It encourages positive social interactions and helps students develop a sense of teamwork and interpersonal relationships (Butt et al., 2020). Cognitively, cooperative learning can enhance students' understanding of PE concepts, strategies, and tactics by engaging them in group discussions, problem-solving, and decision-making processes. It promotes critical thinking, creativity, and metacognitive skills as students learn from and with their peers (Bores-Garcia et al., 2021; Fyall & Metzler, 2019). Overall, the papers likely concluded that cooperative learning is an effective instructional approach in PE that can contribute to students' holistic development (Jain et al., 2025). By addressing physical, emotional, social, and cognitive aspects, cooperative learning can create a more inclusive, engaging, and meaningful learning experience for students. While the specific conclusions of each paper may vary depending on the study's context, methodology, and focus, the collective evidence suggests that cooperative learning has the potential to positively impact various aspects of student development in PE when implemented effectively (Benavides et al., 2020).

2.2 Social Interdependence Theory and Collaborative Learning

Through PE classes, students can develop basic abilities that may enable them to become members of society (Ahmad et al., 2024). It is essential to become a competitive adult. PE is one of the few subjects in education that helps students improve their cognitive, affective and psychomotor skills and allows them to interact with their classmates and play a variety of social roles. PE develops students' social skills, such as respect, tolerance and interpersonal relationships, as well as team cohesion, such as cooperation and group dynamics (Wicagsono & Al, 2023). Additionally, students learn how to support social cognitive development and enhance their sense of self-worth and confidence. Emphasizing team PE has benefits for organizational performance, such as improving job performance, personal health, and team cohesion and performance according to Cojocaru et al. (2022). At the same time, it also talked about the responsibility of PE to society. PE contributes to students' social skills, problem-solving skills, emotional intelligence, time management, teamwork, teamwork, and problem-solving skills. PE can also help children develop a positive attitude towards training and physical activity, allowing them to participate in a variety of different PE activities. In PE teaching, teamwork and interaction can affect students' futures. Enhancing team cohesion requires the design and implementation of PE courses (Bujang et al., 2020).

2.3 The Relationship between IoT and Learning Outcomes in Learning PE

The IoT is becoming a revolution in the contemporary world and has achieved important milestones in the field of AI. The concept of IoT can be illustrated with a simple example from our daily lives, such as television. For example, we can change channels remotely through the remote control without touching the TV. The core concepts of IoT remain consistent and we can remotely control almost every appliance around us. The IoT is a technology with far-reaching implications in terms of how we react and behave every day. From common home appliances and remote-control devices to transportation that provide the shortest and safest route, all can be controlled from smartphones, including our smartwatches (Butt et al., 2020). The IoT forms a huge network, including various devices connected. These connected devices collect data, share operational information, and perform assigned tasks.

In this process, the key role of sensors cannot be ignored. Sensors are embedded in our phones, various appliances, and signal-based devices connected to the IoT. The IoT ecosystem involves Internet-connected smart devices using integrated systems, including processors, sensors, and communication hardware, to collect, transmit, and process the data they acquire. IoT devices expose sensor data through the use of IoT portals or other edge devices. Afterward, they can transfer the data to the cloud or analyze it locally. These devices then communicate with other devices on the network and take actions based on what they learned from each other (Benavides et al., 2020). Devices can perform most tasks on their own without the need for human hands. However, they can still communicate with humans to access data, set settings, and give instructions.

The specific IoT applications installed have a significant impact on the connectivity, networking, and communication protocols used by these connected smart devices (Jain et al., 2025) The situation and constraint theory perspectives of have a closer look at how various situational factors in learning and gaming environments interact to influence players' goal orientations. These views view games as relational, meaning there is a connection between the player and the environment (Butt et al., 2020). When solving tactical challenges, players must adopt specific functional behaviors that satisfy the interacting participants, the environment, and task constraints. The situated learning perspective holds that creating and sustaining social environments and interpersonal interactions for learning are indispensable because they allow people to enjoy the learning process and play. Therefore, social interaction, institutional culture and body perception influence learning (Ahmad et al., 2024). According to this view, the information-motor coupling when players solve problems in the game is affected by the interaction between the body's perceptual domain and the cognitive domain

2.4 The Relationship between Cloud Computing and Learning Outcomes in Learning PE

In addition to firmly supporting first-class education, the educational goals of the 21st century also turn to cultivating students' creativity and abilities (Bujang et al., 2020). The creation and development of cloud platforms and cloud hosting are entering a golden period of education and teaching reform. With the development of education in the information age, teaching methods and learning resources are also constantly changing (Qureshi et al., 2020). PE has become a national strategy for emerging countries and is crucial to realizing the great rejuvenation of the Chinese nation and realizing the Chinese dream. Developing national fitness is the key to promoting the historical progress of China and the world (Teo et al., 2021). Despite the digitization of education, our PE teaching methods and resources still rely on words and deeds, which are unable to meet the expanded needs of PE and health courses. The concept of cloud hosting is that while the creation of personal space is continuously improved, the functions of cloud hosting also be improved (Wicagsono & Ai., 2023).

The education system is the primary method of developing students' potential and ensuring that they become pillars of society (Costa et al., 2021). The development of informatization in university teaching has had a significant impact on the traditional teaching model, which must be reformed. At the same time, the natural combination of computer networks and academic teaching is a new development trend. In PE, technological methods have traditionally dominated the teaching of physical activity and movement (Jain et al., 2025). Through this teaching form, teachers plan a series of prescriptive exercises based on simulations of game parts and guide students through direct commands. Different missions have a specific goal, usually aligned with the development of some technical skill inherent to the game. Therefore, this approach assumes that a certain level of skill must be acquired before performing the activity (Cojocaru et al., 2022).

However, mastering a game requires much more than just physical or technical skills (Cojocaru et al., 2022). Over the years, we have found that one of the main criticisms of this approach is that it does not serve all students, as it can only be developed effectively in the most proficient students; over-reliance on teacher-provided guidance limits student autonomy in the game Choices are acquired and, most importantly, the resulting learning is divorced from real games, making decision-making difficult in-game practice (Vonitsanos et al., 2024). Teachers and researchers in the field of PE have been working for many years to introduce alternative approaches to movement education (Butt et al., 2020). Based on the ideas of educational models, these new proposals have developed greatly in recent years. However, their origins date back to the 1970s, when proposals focused on tactics began to emerge (Chanthiran et al., 2022). These alternative models focus on students' cognitive development and skill-building through decision-making in games (Benavides et al., 2020). Learning no longer focuses on overcoming specific goals but instead focuses on students solving problems in real competition situation. It is based on these ideas that the Teaching Games for Understanding (TGfU) model came into being (Ahmad et al., 2024).

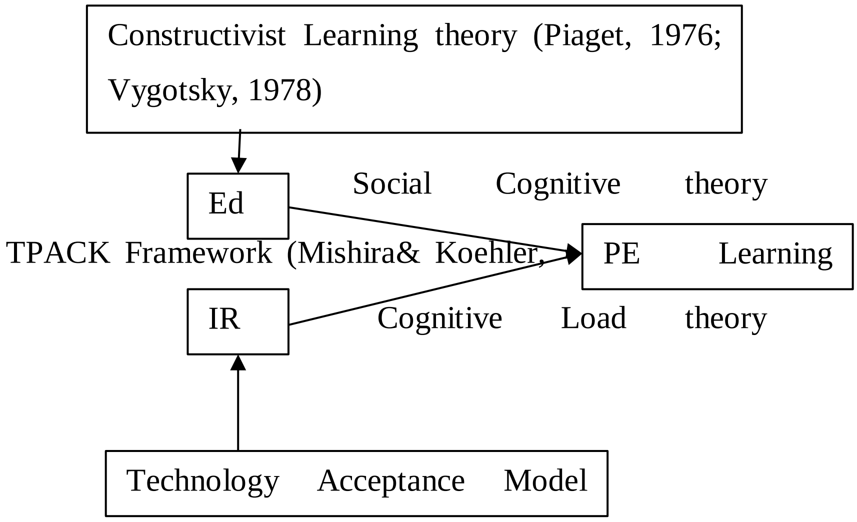

Figure 1: Theoretical Framework

Figure 1 shows the integration of Industry 4.0 and Education 4.0 technologies in Physical Education is comprehensively supported by a multi-faceted theoretical framework. Constructivist Learning Theory highlights how immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) promote active, experiential learning, enhancing motor skills and cognitive understanding.

a. The Technology Acceptance Model (TAM) explains the adoption of devices such as Internet of Things (IoT), Big Data analytics, and Cloud Computing in PE, emphasizing perceived usefulness and ease of use.
b. Social Cognitive Theory underscores the role of VR and AR in boosting self-efficacy and observational learning in technology-enhanced PE environments.

Cognitive Load Theory provides guidance for designing effective Big Data and Cloud Computing applications that manage information presentation for optimal learning. Finally, the TPACK framework is crucial for understanding how PE teachers can effectively combine technological, pedagogical, and content knowledge to integrate these diverse technologies. This robust theoretical foundation allows for a nuanced understanding of how VR, AR, IoT, Big Data, and Cloud Computing collectively transform and enhance PE learning outcomes.

3. Research Methodology

This study utilized a quantitative research design to thoroughly investigate the intricate relationship between Industry Revolution 4.0 (IR 4.0) technologies, Education 4.0 (Ed 4.0), and Physical Education (PE) among university students in Heilongjiang, China. The research process began with the careful selection of a design that ensured a focused and in-depth understanding of these three core elements. A purposive sampling method was employed to select PE-major students from Harbin Sports College in Heilongjiang, ensuring the representativeness of the findings within this specific region. The primary tool for data collection was structured questionnaires, chosen to guarantee the reliability and breadth of the information gathered.

Throughout the entire research process, strict adherence to ethical considerations was paramount. All data collection and analysis procedures meticulously followed relevant ethical standards, prioritizing the respect and protection of participants' rights and privacy. Researchers maintained transparency regarding their methods and actively mitigated potential ethical risks. This comprehensive approach, detailing the research design, population, instruments, data collection, and ethical protocols, establishes a robust foundation for the empirical investigation, setting the stage for a systematic exploration and insightful analysis of the research topic.

3.1 Research Design

The chosen research methodology for this study is a quantitative cross-sectional design. This approach systematically gathers and analyzes numerical data to explore the relationships between IR 4.0 technologies, Education 4.0, and Physical Education learning outcomes in Heilongjiang, China. The quantitative nature is ideal due to the specific and measurable research questions, enabling the generalization of findings to a broader population and informing educational policies. It facilitates the use of statistical techniques to measure variables, mediation effects, and identify significant patterns and correlations, providing a robust foundation for evidence-based conclusions.

Within this quantitative framework, a cross-sectional design was selected because it allows for data collection from participants at a single point in time, offering an immediate "snapshot" of the current status of PE amidst IR 4.0 and Ed 4.0 integration in Heilongjiang. This design is highly efficient and resource-friendly, crucial in the rapidly evolving fields of technology and education. Furthermore, it directly aligns with the study's objectives to investigate the current impact of specific technologies on PE learning outcomes, permits comprehensive statistical analysis of these relationships, and supports the generalizability of the findings to a wider population, thereby providing timely and relevant insights.

3.2 Sampling

The study employs a robust sampling strategy combining stratified random sampling and purposive sampling to comprehensively understand the impact of IR 4.0 and Ed 4.0 technologies on PE learning outcomes among students at Harbin Sports College in Heilongjiang, China. The target population consists of 6,430 PE-related major students. Initially, purposive sampling was used to categorize students into four relevant strata: Physical Education, Sports Training, Sports Management, and Sports Medicine. This ensured a diverse representation of PE disciplines, aiming for breadth rather than direct group comparison. Subsequently, stratified random sampling was applied within each stratum, with a sample size of 363 students determined using Cochran's formula (95% confidence level, 5% margin of error). This method, leveraging a random number generator for selection within each stratum, ensures an unbiased and representative sample, enhancing the validity and generalizability of the findings within the specific context of the college.

The strategic use of purposive sampling, particularly "expert sampling" by focusing on PE-related majors, is justified by the need for in-depth insights from individuals with extensive professional knowledge and practical experience in PE. This approach allows for a rich understanding of student perspectives on the integration of IR 4.0 technologies. While acknowledging that this may limit the generalizability to the broader Chinese PE student population, the detailed demographic data collected including gender, age, ethnic identity (Han and ethnic minorities), type of PE major, and family income enriches the sample profile and strengthens the reliability of the study within Heilongjiang's unique socio-cultural and educational landscape. This meticulous sampling strategy, further guided by considering factors like student grade level and diverse backgrounds, ensures the scientific rigor and applicability of the research findings for future PE reforms.

4. Finding and Discussion

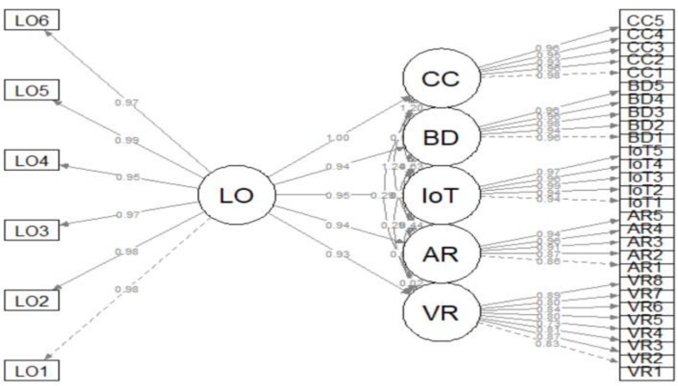

Figure 2. Path diagram

In summary, the SEM results provide strong support for all six hypotheses, demonstrating the significant positive impact of VR, AR, IoT, Big Data, and Cloud Computing technologies on PE learning outcomes among students in Heilongjiang, China. The analysis also highlights the interrelationships among these technologies, suggesting that they work together to create a comprehensive and effective learning environment in physical education. The Structural Equation Modeling (SEM) analysis from students revealed complex relationships between emerging technologies and PE Learning Outcomes, with significant direct effects and potential mediating relationships. Cloud Computing demonstrated the strongest positive relationship with Learning Outcomes (β = 0.996, SE = 0.0155, $p < .001$), with a 95% confidence interval ranging from 0.959 to 1.020. This nearly perfect effect underscores the fundamental role that cloud infrastructure plays in modern PE education, enabling seamless access to learning resources and facilitating collaborative learning environments.

Internet of Things showed a robust positive relationship with Learning Outcomes (β = 0.946, SE = 0.0233, $p < .001$), with a 95% confidence interval ranging from 0.861 to 0.953. The narrow confidence interval and low standard error suggest highly reliable results, indicating that IoT technology consistently enhances PE learning through real-time monitoring and feedback systems. The results also show strong positive relationships between Big Data and Learning Outcomes (β = 0.937, SE = 0.0275, $p < .001$), with a 95% confidence interval ranging from 0.865 to 0.973. This substantial effect highlights the crucial role that data analytics plays in personalizing and optimizing PE instruction for students.

Virtual Reality and Augmented Reality demonstrated similar strong effects on Learning Outcomes (VR: β = 0.934, SE = 0.0388, $p < .001$, CI: 0.715-0.867; AR: β = 0.935, SE = 0.0379, $p < .001$, CI: 0.739-0.888). These parallel findings suggest that immersive technologies are equally effective in enhancing PE learning experiences, likely through their ability to provide detailed visualization and practical demonstration capabilities. The path diagram reveals significant intercorrelations among all five technological factors, suggesting potential synergistic effects. The strong factor loadings (ranging from 0.73 to 0.98) for all measurement items indicate robust construct validity. These correlations suggest that the technologies may work most effectively when implemented in combination rather than in isolation.

Regarding the research objectives, all five technologies demonstrate significant positive impacts on PE learning outcomes, with Cloud Computing showing the strongest effect. The consistent pattern of strong positive relationships suggests that digital transformation in PE education yields substantial benefits. However, to fully understand the mechanisms of these effects, further analysis of potential mediating and moderating variables would be valuable. The current results do not provide information about interaction effects between these technologies, which could be an important area for future research. Future research should explore the mechanisms underlying these effects by examining potential mediating and moderating variables. Additionally, investigating the interaction effects between different technologies would provide valuable insights into how these systems work together and influence outcomes. This would deepen our understanding of the complex relationships at play. The findings have important implications for PE education policy and practice at. The strong positive effects across all technologies suggest that a comprehensive digital transformation strategy, rather than piecemeal implementation of individual technologies, might be most beneficial for enhancing learning outcomes.

5. Conclusion and Recommendation

5.1 Implication

The study's findings highlight the multifaceted nature of digital transformation in physical education, demonstrating significant positive effects from all technological factors on learning outcomes. The exceptionally strong impact of Cloud Computing (β = 0.996) challenges existing assumptions, emphasizing its foundational role as an essential infrastructure prerequisite for successful digital transformation in practical educational contexts. Furthermore, the remarkably similar effects of Virtual Reality (VR) and Augmented Reality (AR) suggest their complementary roles in enhancing PE learning, necessitating a re-evaluation of theoretical models that might treat them as alternative solutions. The strong intercorrelations among all technologies underscore the presence of synergistic effects, indicating a need for more sophisticated theoretical frameworks that can capture these complex interactions and their collective impact on learning outcomes.

These insights translate into clear practical and policy implications for enhancing PE education in Chinese higher education, particularly in Heilongjiang. Institutions should prioritize the development of robust cloud computing infrastructure, including high-speed networks and data centers, while also investing in comprehensive IoT and Big Data analytics systems for performance monitoring and personalized instruction. Policies should support the integrated implementation of VR and AR for comprehensive visualization and demonstration capabilities. Crucially, successful digital transformation requires comprehensive professional development programs for PE instructors, focusing on both technical skills and pedagogical guidance for technology-enhanced teaching. Ultimately, integrated approaches to technology adoption, supported by systematic monitoring and evaluation, are recommended to maximize the benefits of digital transformation in PE education, ensuring sustained effectiveness and adaptability to evolving technological landscapes.

5.2 Future Research

This study offers valuable insights into the complex interplay between emerging technologies and PE learning outcomes, advocating for a holistic approach to digital transformation that encompasses both infrastructure development and specialized technological solutions. Future research should build on these findings by employing longitudinal designs to understand the dynamic evolution of technology-enhanced learning, conducting cross-institutional comparisons to assess generalizability across diverse contexts, and utilizing mixed-method approaches to gain deeper qualitative insights into student and instructor interactions with technology. While acknowledging limitations such as external confounding factors, the rapid pace of technological advancements, the specific institutional context, and reliance on self-reported data, the study lays a strong foundation. Further research should focus on optimizing technology integration strategies, exploring the interaction between traditional and digital instruction, and examining the broader impacts of technology-enhanced PE on student development, ultimately guiding informed decisions for maximizing educational effectiveness and pedagogical quality.

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Conflict of Interest

The authors declare no conflicts of interest.

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