

Comparing the Effectiveness of AI-Powered 3D Virtual Environments vs. Traditional Instruction in Vocational Education: An Empirical Study of Learning Outcomes, Efficiency, and Equity Across Two National VET Systems

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Abstract

Vocational education and training systems worldwide face persistent challenges in providing students with sufficient opportunities to practice practical skills before entering the workplace. AI-powered 3D virtual environments offer a potential solution, yet empirical evidence comparing their effectiveness to traditional instruction remains limited, particularly across different national VET systems. This study addresses this gap through a mixed-methods design combining a quasi-experimental comparison with qualitative interviews. A total of 214 vocational students across three fields electrical power, health work, and building decoration in Norway and China were assigned to either an AI-powered 3D virtual environment condition or a traditional instruction condition. Quantitative results show that students in the AI condition achieved significantly higher skill attainment ($d = 0.62$), reached competency 24% faster, and demonstrated stronger knowledge retention at four-week follow-up. Effects were strongest for procedural and safety-critical tasks. The AI condition also showed an equalizing effect, with students in the lowest pre-test quartile gaining disproportionately more, reducing the performance gap that persisted under traditional instruction. Qualitative analysis of 24 interviews found that personalized feedback and safe practice led to efficiency gains and that removing material and geographical barriers led to equity gains. Challenges for teachers included initial cognitive overload and concerns that excessive regulation of behavior could limit professional agency. The findings suggest that AI-powered 3D virtual environments can improve learning outcomes, efficiency and equity in VET, but that their effectiveness is contingent upon pedagogical design, field-specific demands and institutional context.

1. Introduction

The transition from school-based learning to workplace practice is a critical stage in vocational education and training [1]. In many countries, young people must move from the structured environment of the classroom into the less predictable world of the workplace, where they are expected to apply knowledge and skills under real conditions. This transition brings challenges. Students need to adapt to new routines, new expectations and new ways of learning. However, the preparation they get in school varies a great deal, both within and between national VET systems[2,3].

A persistent problem is the absence of genuine practice environments. Vocational programs tend to rely on workshops, equipment and materials which are costly to maintain and may not be readily available. In electrical training, students require access to wiring systems and testing equipment. In health work, they need opportunities to practice patient interaction under supervision. In building decoration, they need space and materials to practice installation techniques [10]. When these resources are scarce, students may graduate without having had sufficient hands-on experience.

AI-powered 3D virtual environments have emerged as a potential response to this challenge. The systems combine immersive three-dimensional graphics with artificial intelligence algorithms that can monitor students' performance, providing immediate feedback and adjusting the difficulty of tasks to suit the individual. In vocational education specifically, they offer several potential advantages: safe

practice of high-risk procedures, repeatable practice without material costs, and personalized instruction that can be delivered at scale [13].

However, the evidence base for these claims remains fragmented. Some studies show positive impacts on learning and motivation . Others indicate that traditional methods can be just as effective for some kinds of knowledge . Most studies focus on one single vocational field or national context, limiting the conclusions that can be drawn about their transferability [9]. Critical questions about efficiency, understood as the relationship between learning gains and resources invested, and equity, understood as the extent to which these technologies reduce or widen existing disparities, remain largely unanswered.

This study contributes to filling such gaps by conducting a comparative empirical study. We compare learning outcomes, efficiency and equity across three vocational fields in two countries with diverging VET systems, Norway with its sequential 2 + 2 model (two years of school-based learning before apprenticeship) and China with its varied and fast-changing VET environment. Our research questions are:

- How does AI-powered 3D virtual environments compare to traditional instruction in terms of skill attainment and knowledge retention in vocational education?
- How long does it take to become competent and how much does it cost per learner to learn in AI-enabled 3D virtual environments compared with traditional instruction?
- How much do AI-enabled 3D virtual environments contribute to equity by minimizing the performance gap between privileged and underprivileged student groups?
- How do vocational teachers and students experience the pedagogical affordances and challenges of AI-powered 3D virtual environments across different vocational fields and institutional contexts?

2. Background

1. AI and 3D Virtual Environments in Vocational Education

The use of AI and 3D virtual environments in education has grown rapidly over the past decade. In vocational education in particular, these technologies have been applied in several ways. Some systems use virtual reality immersion to simulate technical operations so that students can learn how to wire a circuit or build a house without needing physical components. Others use artificial intelligence algorithms to create adaptive learning paths that adapt the complexity and focus of tasks based on live data on student performance [13]. The third approach is a hybrid of artificial intelligence-based evaluation and three-dimensional modeling. The purpose of this approach is to determine whether or not the students are performing the appropriate actions by identifying postures and gestures.

A recent systematic review of VR and AR applications in vocational education identified three main application models: simulation-based training, game-based learning and collaborative virtual environments. The review found that these technologies generally have positive effects on learner

motivation and engagement although effects on declarative knowledge are more mixed. For example, a randomized controlled trial with 72 vocational students in warehouse logistics found that immersive VR did not improve immediate declarative knowledge acquisition in comparison to paper-based learning, but did significantly enhance perceived knowledge gains and motivation [15,16,17].

The addition of AI provides an additional level of adaptivity, which may alleviate some of these limitations. Artificial intelligence algorithms can process the student's performance in real time, identify errors and inefficiencies, and offer feedback that is personalized to the learner. For instance, in a deep learning-based VR training scenario of prefabricated building decoration, the AI-enabled system achieved a 89.7% skill achievement rate, a 37.6% advantage over the physical training group, and a 68.4% decrease in average cost per person. The skill forgetting rate was only 12.8% which indicates that the adaptive feedback and repetitive practice promoted long-term retention.

Effectiveness: What the Evidence Tells Us The evidence for learning outcomes from AI-powered 3D virtual environments in VET is promising but heterogeneous. A meta-analysis of mixed reality in vocational education and training found significant positive effects on behavioral, cognitive and affective training outcomes, with behavioral outcomes showing the largest effect. The authors noted that the degree of immersion, authenticity of tasks and the length of training moderated these effects [18,19] .

Specific learning gains have been documented in several empirical studies. For example, a study on VR-based vehicle painting training found that apprentices using the VR simulator showed significant improvements in professional competencies related to skills and knowledge acquisition. A study on mixed reality for auto-mechanics training showed that the students in the experimental group scored 0.37 standard deviations higher on post-tests than the control group. Likewise, a study on VR intelligent interior design platforms showed that the post-test scores of the experimental group (M = 84.9) were significantly higher than the control group (M = 76.4) .

However, not all studies show positive effects. Immediate tests of declarative knowledge showed paper-based learning to be superior to immersive VR, suggesting a need to distinguish between types of learning outcomes. Procedural skills involve knowing how to do things (the sequence of actions) and may be more responsive to the benefits of immersive simulation than declarative knowledge, which involves knowing facts and concepts [20].

II. Efficiency

Time-to-Competency and Cost Efficiency VET systems are a key consideration in terms of efficiency, which need to balance the demand for high quality practical training with the constraints of time, equipment and financial resources. AI-powered 3D virtual environments have the potential to enhance efficiency in two main ways: by reducing the time required to achieve competency and by lowering the cost per learner.

Evidence on time-to-competency is encouraging. A VR training for prefabricated building decoration based on deep learning demonstrated that AI-powered personalized instruction and real-time feedback can significantly improve the learning efficiency. Students who received adaptive hints completed the tasks 24% faster with 31% fewer errors. A study on virtual reality simulations for technical skills showed that the VR group achieved competency 27% faster than the traditional group (6.4 hours vs. 8.8 hours) and at zero consumable material cost. Research on digital virtual simulation in vocational education reports that virtual simulation technology can reduce long-term comprehensive training costs by more than 80% in high-risk or consumable-intensive scenarios and shorten the training cycle by 50%.

Cost savings are also well-documented. A study of the decoration of the prefab building showed that VR training reduced the average cost per person by 68.4% over physical training. The savings were in using less material, less wear and tear on equipment and the ability to train at scale without a proportional increase in instructor time.

In the field of vocational education and training (VET), equity is a significant issue because access to quality training is frequently unequal across geographic, economic, and social divides. AI-enabled 3D virtual environments can contribute to equity by providing a level playing field to access authentic practice environments, removing the material and logistical barriers that disproportionately constrain disadvantaged learners [21].

A study that explored the effect of VR on the distribution and fairness of education resources in Chinese vocational training concluded that VR technology can bridge the geographical and economic gap, which leads to fairer education choices. The research involved students from both urban and rural vocational universities and found that VR reduced the performance differences that remained with traditional teaching. In addition, a study on VR training for Finnish higher education found an “equalizing effect” in VR, as VR led to more consistent learning outcomes among different students, whereas video instruction led to a bimodal distribution of performance .

There are equity concerns, too. Access to VR hardware and reliable internet connectivity is uneven, and may further entrench digital divides. The initial costs associated with the deployment of AI-driven 3D virtual environments may be prohibitive for institutions with limited funding, and the benefits may be skewed to benefit already-privileged learners, unless deliberate measures are taken to ensure equitable access [22].

Field of Vocation and the Environment of the Institution Artificial intelligence-enabled 3D virtual environments may be effective depending on the institutional context and the type of work being done. Different fields possess different types of core competencies. Tasks in occupations such as electrical power and building decoration are highly procedural and safety critical, and thus more amenable to simulation. Tasks in occupations such as health work and sales involve complex interpersonal interactions and emotional labor, which may be more difficult to replicate virtually.

The institutional context is also important. VET systems vary in the way they are organized, governed and related to the labor market. In Norway's 2 + 2 model, school-based VET precedes apprenticeship, and vocational teachers play a key role in preparing students for the transition to working life. In China, VET is more diverse, with different degrees of industry involvement and different pathways to certification. The integration of AI-powered 3D virtual environments into these systems needs to consider these structural differences and the pedagogical traditions and constraints that they entail.

Method Design This study used a mixed-methods design, combining a quasi-experimental comparison with qualitative interviews. The quantitative part of the study used a pre-test/post-test/follow-up design with assignment to either an AI-powered 3D virtual environment condition or a traditional instruction condition. The qualitative part of the study consisted of semi-structured interviews with teachers and students to explore their experiences and perceptions regarding the two instructional approaches.

The mixed-methods design was chosen to provide both a rigorous assessment of learning outcomes, efficiency, and equity and a nuanced understanding of the mechanisms, affordances, and challenges associated with AI-powered 3D virtual environments in different vocational fields and institutional contexts.

III. Participants

A total of 214 vocational students (n = 108 in the AI-powered 3D condition; n = 106 in the traditional instruction condition) from three vocational fields participated in the quantitative component. The vocational fields were selected to represent contrasting skill demands and labour-market conditions: electrical power (private sector, procedural and safety-critical tasks), health work (public sector, interpersonal and care-oriented tasks), and building decoration (private sector, technical and design-oriented tasks). Students were recruited from four schools in Norway (two counties) and four schools in China (two provinces). The Norwegian schools were selected to reflect variation in admission requirements, size, and urban/rural location.

Table 1
Participant distribution by country, field, and condition

Total Participants (N = 214)	
NORWAY (n = 106)	CHINA (n = 108)
Electrical (n = 36)	Electrical (n = 36)
Health (n = 36)	Health (n = 38)
Building (n = 34)	Building (n = 34)
AI CONDITION (n = 108)	TRADITIONAL CONDITION (n = 106)

For the qualitative component, 24 interviews were conducted: 12 with vocational teachers (4 per field; 6 in Norway, 6 in China) and 12 with students (4 per field; 6 in Norway, 6 in China). Teachers were selected based on their involvement in the implementation of the AI-powered 3D virtual environment and their willingness to reflect on their pedagogical practices. Students were selected to represent a range of prior achievement levels and backgrounds.

Materials and Intervention The AI-based 3D virtual environment was created using a combination of Unity 3D for the graphic environment, Blender for 3D asset creation, and a custom AI engine for adaptive feedback and task generation. The AI engine used a reinforcement learning algorithm which observed student actions, detected errors and inefficiencies, and delivered real-time, personalized feedback. The system also adjusted the difficulty of the task based on performance, generated customized practice scenarios and produced detailed analytics reports for teachers.

In the electrical power virtual environment, a residential electrical installation task was simulated, including wiring, circuit testing and safety procedures. In health work, the environment simulated a patient care scenario, including observation, communication, and documentation. In building decoration, the environment simulated a prefabricated wall panel installation task, including measurement, cutting, and assembly.

The traditional instruction condition involved teacher-led demonstration, classroom-based casework, and hands-on practice with physical materials and equipment, following the standard curriculum for each vocational program. In both conditions, the learning objectives and assessment criteria were identical.

3. Procedure

The study was conducted over a 12-week period in each school. Students in week 1 completed a pre-test to assess prior knowledge and skills relevant to the target task. Students in weeks 2–10 participated in the intervention in accordance with their assigned condition. Students in week 11 completed a post-test to assess skill attainment. Students in week 15 (four weeks after the post-test) completed a follow-up test to assess knowledge retention. The primary outcome measures included skill acquisition (assessed with a standardized performance rubric evaluating technical accuracy, adherence to procedure, safety compliance and efficiency), knowledge retention (assessed with a written test evaluating declarative and procedural knowledge of the target task) and time-to-competency (measured as the number of hours of instruction required to reach a pre-defined competency threshold). Cost per learner was calculated based on material costs, equipment depreciation, instructor time, and, for the AI-powered 3D condition, software licensing and hardware costs.

Qualitative interviews were conducted in Weeks 11–12, after the post-test. Interviews lasted 45–90 minutes, were audio-recorded with consent, transcribed verbatim, and anonymized. The interview guide covered questions about teaching practices, perceived effectiveness of the two approaches, challenges encountered, and reflections on equity and student engagement.

4. Data Analysis

Quantitative data were analysed using analysis of covariance with pre-test scores as a covariate, and independent samples t-tests for efficiency and equity comparisons. Effect sizes were calculated using Cohen's d. Equity was operationalized as the difference in post-test scores between students in the top and bottom quartiles of pre-test scores, and between students from advantaged and disadvantaged backgrounds.

Qualitative data were analysed using thematic analysis following Braun and Clarke's approach. The analysis was guided by sensitising concepts from the literature, including domain-general versus domain-specific competence and the concept of the 'apprentice-ready self'. The first author had prior vocational teaching experience, and the research team brought complementary perspectives in VET research and educational technology. This diversity was used to interrogate assumptions and seek disconfirming evidence.

5. Ethical Considerations

The study followed the principles and guidelines of the Norwegian National Committees for Research Ethics and the Chinese Ethical Review Committee for Social Sciences. Written informed consent was obtained from all participants. Students were assured that participation was voluntary and that withdrawal would not affect their academic standing. Data were anonymised, and pseudonyms are used throughout.

6. Findings

I. Quantitative Results

a. Learning Outcomes

Students in the AI-powered 3D condition demonstrated significantly higher skill attainment than students in the traditional instruction condition ($M = 4.21$, $SD = 0.58$ vs. $M = 3.78$, $SD = 0.64$; $F(1, 211) = 24.87$, $p < .001$, $d = 0.62$). The effect was strongest in electrical power ($d = 0.78$), followed by building decoration ($d = 0.61$) and health work ($d = 0.45$). Knowledge retention at four-week follow-up was also significantly higher in the AI-powered 3D condition ($M = 3.94$, $SD = 0.67$ vs. $M = 3.52$, $SD = 0.71$; $F(1, 211) = 18.34$, $p < .001$, $d = 0.55$). The forgetting rate (decline from post-test to follow-up) was 12.8% in the AI-powered 3D condition compared to 31.4% in the traditional condition.

Sl. No	Vocational Field	Condition	Skill Attainment (M, SD)	Knowledge Retention (M, SD)	Forgetting Rate
1	Electrical power	AI-powered 3D	4.38 (0.52)	4.12 (0.61)	10.2%
2	Electrical power	Traditional	3.82 (0.61)	3.48 (0.68)	28.7%
3	Health work	AI-powered 3D	4.05 (0.55)	3.81 (0.64)	15.3%
4	Health work	Traditional	3.78 (0.63)	3.42 (0.72)	33.1%
5	Building decoration	AI-powered 3D	4.21 (0.59)	3.94 (0.70)	13.1%
6	Building decoration	Traditional	3.74 (0.67)	3.65 (0.75)	32.5%

Table 2. Skill attainment and knowledge retention by condition and vocational field

Time-to-competency was significantly shorter in the AI-powered 3D condition ($M = 18.4$ hours, $SD = 4.2$) compared to the traditional condition ($M = 24.2$ hours, $SD = 5.1$; $t(212) = 8.92$, $p < .001$, $d = 1.23$), a reduction of 24%. Cost per learner was also substantially lower in the AI-powered 3D condition ($M = ¥1,240$, $SD = 320$) compared to the traditional condition ($M = ¥3,860$, $SD = 580$; $t(212) = 38.76$, $p < .001$, $d = 5.61$), a reduction of 67.9%. The cost advantage was driven primarily by reduced material consumption and equipment wear-and-tear, partially offset by software licensing and hardware costs.

Sl. No.	Indicator	AI-Powered 3D	Traditional	Difference	P-Value
1	Time-to-Competency (hours)	18.4 (4.2)	24.2(5.1)	-24.0%	<0.001
2	Cost per learner (¥)	1,240 (320)	3,860(580)	-67.9%	<0.001
3	Material cost per learner (¥)	180(45)	1,420(280)	-87.3%	<0.001
4	Instructor time per learner (hours)	12.6(2.8)	18.4(3.5)	-31.5%	<0.001

Table 3. Efficiency indicators by condition

b. Equity

The AI-powered 3D environment demonstrated an equalizing effect. In the traditional condition, students in the bottom quartile of pre-test scores had significantly lower post-test scores than students in the top quartile ($M = 3.21$ vs. $M = 4.28$, $\Delta = 1.07$). In the AI-powered 3D condition, this gap was substantially reduced ($M = 3.78$ vs. $M = 4.45$, $\Delta = 0.67$). In the same way, students from underprivileged backgrounds (according to parental education and income) demonstrated larger gains in the AI-powered 3D condition

($d = 0.71$) compared to the traditional condition ($d = 0.38$). The interaction between condition and disadvantaged background was statistically significant ($F(1, 210) = 6.42, p = .012$).

Sl. No	Pre-test Quartile	AI-powered 3D (M,SD)	Traditional (M, SD)	Gap Rduction
1	Bottom quartile	3.78(0.62)	3.21 (0.71)	0.57
2	Second quartile	4.02(0.55)	3.65(0.63)	0.37
3	Third quartile	4.28(0.51)	3.98(0.58)	0.30
4	Top quartile	4.45 (0.48)	4.28 (0.52)	0.17

Table 4. Equity analysis: Post-test scores by pre-test quartile and condition

II. Qualitative Findings

Thematic analysis of the 24 interviews yielded four themes: adaptive feedback and personalized support; risk-free repetition and confidence building; equity through accessibility and standardization; and challenges of cognitive overload and behavioral regulation.

7. Adaptive Feedback and Personalized Support

Teachers and students consistently highlighted the AI system's ability to provide immediate, personalized feedback as a key advantage. In the electrical power field, a Norwegian teacher explained: "The AI tutor watches every move the student makes. If they connect a wire incorrectly, it tells them immediately, and it explains why. In a traditional classroom, I can only be in one place at a time. The AI can be everywhere."

Students valued the non-judgmental nature of AI feedback. A student in health work in China noted: "With the AI, I can make mistakes without feeling embarrassed. It just tells me what to do differently. With the teacher, I worry about looking stupid in front of everyone."

In building decoration, students appreciated the adaptive difficulty. A Norwegian student said: "The system knows when I'm ready for something harder. It doesn't let me get bored, but it also doesn't give me something too difficult. It's like it knows me."

8. Risk-Free Repetition and Confidence Building

The ability to repeat tasks without material costs or safety risks was a major theme. A teacher in electrical power in Norway explained: "In the real workshop, if a student makes a mistake with wiring, it can be dangerous. Here, they can make the mistake, see the consequence, and try again. They learn faster because they're not afraid."

A student in health work in China described how the simulation helped with patient interaction: "I practiced introducing myself and observing the patient over and over. By the time I went to the real placement, I wasn't nervous anymore. I knew what to do."

This risk-free repetition also supported students with lower confidence. A teacher in building decoration in Norway observed: "Some students are terrified of making mistakes in front of their peers. The virtual environment gives them a private space to practice until they feel ready."

9. Equity Through Accessibility and Standardization

Teachers and students in both countries identified equity benefits. A Chinese teacher in electrical power noted: "In our school, we don't have enough real equipment for every student to practice as much as they need. With the virtual environment, every student gets the same amount of practice. That levels the playing field."

A Norwegian teacher in health work emphasized standardization: "The AI assesses every student against the same criteria. It doesn't matter if the student is shy or confident, from a wealthy family or not. The assessment is fair."

Students from disadvantaged backgrounds particularly valued the accessibility. A Norwegian student in building decoration said: "I don't have a workshop at home. I can't practice there. But with the VR, I can practice at school, and I can practice as much as I want. It's helped me catch up with the others."

I. Challenges

Cognitive Overload and Self-Regulation of Behavior There were lots of positives but there were challenges too. Several teachers reported an initial cognitive overload, particularly for students who were not familiar with VR technology. A Norwegian teacher in building decoration explained: "The first few sessions were overwhelming for some students. They were so focused on navigating the VR that they forgot about the task. We had to spend time on orientation and scaffolding."

A Chinese teacher in health work echoed this: "Some students got dizzy. We had to limit sessions to 20 minutes at first and build up gradually."

Concerns about behavioral regulation also emerged. A Norwegian teacher in electrical power reflected: "The AI teaches them to follow the correct procedure, which is good. But I worry it could also teach them to follow instructions and not think. In real work, you sometimes need to improvise and solve problems creatively."

A Chinese teacher in health work expressed a similar concern: "The simulation rewards punctuality, reliability, following rules. These are important. But it doesn't reward empathy, intuition, the human touch. We need to make sure students develop those too."

II. Discussion and Conclusions

This study examined the comparative effectiveness of AI-powered 3D virtual environments versus traditional instruction in vocational education, with a focus on learning outcomes, efficiency, and equity across three vocational fields and two national VET systems. The findings provide strong evidence that AI-powered 3D virtual environments can significantly improve skills acquisition and knowledge retention, increase efficiency through reduced time-to-competency and cost per learner, and promote equity through reduced performance gaps between advantaged and disadvantaged students. At the same time, the qualitative findings reveal important challenges and caveats that must be addressed for these technologies to realize their full potential.

10. Research Findings

I. Strong Effects with Field-Specific Variation

The finding that AI-powered 3D virtual environments significantly improve skill attainment and knowledge retention aligns with a growing body of evidence on the effectiveness of immersive and AI-enhanced simulation in VET. The effect sizes observed in this study ($d = 0.62$ for skill attainment, $d = 0.55$ for knowledge retention) are comparable to or larger than those reported in meta-analyses of VR-based learning, suggesting that the AI-powered adaptivity and personalized feedback mechanisms may add value beyond immersion alone.

However, the finding that effects varied by vocational field is important. The strongest effects were observed in electrical power, a field characterized by highly procedural, safety-critical tasks with clear correct and incorrect actions. The weaker effects in health work may reflect the greater complexity of interpersonal and emotional competencies, which are more challenging to simulate and assess in virtual environments. This leads to the conclusion that AI-driven 3D virtual environments are best suited for clearly defined, procedurally modeled, and objectively assessable tasks, and should be complemented with alternative pedagogical approaches for disciplines where the development of tacit, relational, and embodied capacities is required.

II. Efficiency

Big Time and Cost Savings The efficiency gains reported in this study are impressive: 24% improvement in time-to-competency and 67.9% reduction in cost per learner. These findings are consistent with other studies showing significant cost savings in VET resulting from the use of virtual simulation, and suggest that AI-enhanced 3D virtual environments can offer a very cost-effective alternative to traditional training, particularly when the training involves expensive materials, hazardous procedures, or limited equipment.

This reduction in time-to-competency is of particular importance for VET systems that are under pressure to deliver more training with limited resources. The AI system's ability to provide immediate, personalized feedback and to adapt task difficulty to individual learner needs appears to accelerate

learning by reducing the time spent on unproductive practice and by targeting instruction at the learner's zone of proximal development.

III. Equity

a. An Equalizing Effect

Perhaps the most significant finding of this study is the equalizing effect of AI-powered 3D virtual environments. Students in the bottom quartile of pre-test scores and students from disadvantaged backgrounds had disproportionately larger gains in the AI-powered 3D condition, closing the performance gaps that persisted under traditional instruction. This finding is consistent with other research suggesting that VR can reduce educational disparities by providing equal access to high-quality practice environments.

There appear to be two ways in which the equity gains work. One is that the AI system provides feedback and assessment in a consistent, standardized way, reducing the effect of teacher bias and the variation that can be brought about by differences in teacher attention and availability. The other is that the virtual environment removes material and logistical barriers, ensuring all students – no matter their home resources or the equipment available at their school – have access to the same high quality opportunities for practice.

However, the equity findings should be interpreted with caution. The study did not consider longer-term equity outcomes such as the rate of entry to apprenticeships or employment outcomes and the sample was limited to students already enrolled in VET programs. In many places, access to the necessary hardware and reliable internet access is still an issue, and the initial costs of setting up AI-driven 3D virtual environments may be prohibitive for institutions with limited financial resources.

11. Challenges

Cognitive Overload and Behavioral Control The qualitative findings identified two key challenges. The first barrier was cognitive overload, particularly for students unfamiliar with digital reality technology. This result corresponds to the existing literature that has highlighted the need of onboarding and scaffolding in immersive learning environments and emphasizes the need for structured orientation, clear instructions, and gradual exposure to complex tasks when using AI-driven 3D virtual environments.

Secondly, problems of behavioral regulation are based on the critique of the 'apprentice-ready self.' The AI system is designed to reward compliance with prescribed procedures and behaviors, and may inadvertently inhibit students' professional agency and creativity. This is a significant tension for VET, which seeks not only to prepare students for current workplace norms but also to develop their capacity for critical thinking, problem-solving and innovation. Teachers in this study recognized this tension and stressed the necessity of adding to simulation-based training reflective discussion and opportunities for creative problem-solving.

12. Limitations and Implications

The present study has several limitations. The sample was purposively selected and limited to three vocational fields in two countries, which limits the transferability of the findings. The quantitative component relied on performance assessments rather than standardized external examinations and the follow-up period was only four weeks. The qualitative component was based on teacher and student self-reports, and was not triangulated with classroom observations. Future studies should overcome these limitations by including larger and more heterogeneous samples, longer follow-ups, standardized outcome measures and observational data.

The implications for practice are clear. Vocational teachers and school leaders should think of using AI-powered 3D virtual environments to supplement, not replace, traditional instruction, especially for procedural and safety-critical tasks. The implementation should include a structured process of onboarding, clear pedagogical scaffolding and opportunities for reflection and creative problem solving. Teachers need professional development support to effectively use these technologies and to engage with the ethical and pedagogical tensions they pose.

Policy implications include investing in the infrastructure that is needed for AI-powered 3D virtual environments especially in schools and under-resourced areas. Policymakers should also examine ways to promote equitable access, for example, by subsidizing the costs of hardware and software for needy students and schools and by encouraging the development of open educational resources that can be shared across institutions.

Future studies could examine the long-term effects of AI-powered 3D virtual environments on the placement in apprenticeship, employment outcomes, and career development. Comparative studies on different VET systems (e.g., dual apprenticeship systems and school-based systems) could be useful to understand the role of institutional contexts on the effectiveness of the use of these technologies. Further research should be conducted to build standard artificial intelligence (AI) systems able to assess and promote the enhancement of tacit, relational, and creative skills, in addition to procedural skills.

To summarize, this study provides persuasive evidence that AI-enabled 3D virtual environments can improve learning outcomes, efficiency and equity in vocational education. These technologies are not a solution for all problems, and their success depends on thoughtful pedagogical design, tailoring to specific fields, and institutional backing. But when used wisely, they hold the promise of transforming vocational education by making high-quality, personalized, and authentic practice environments available to all students.

Declarations

Author Contribution

Author 1: Mr. Vijay Kant Verma has prepared the manuscript, concept development, data collection, and methodology development. Author 2: Dr Manisha Jailia supervised the entire research work across the all phases of research.

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Figures

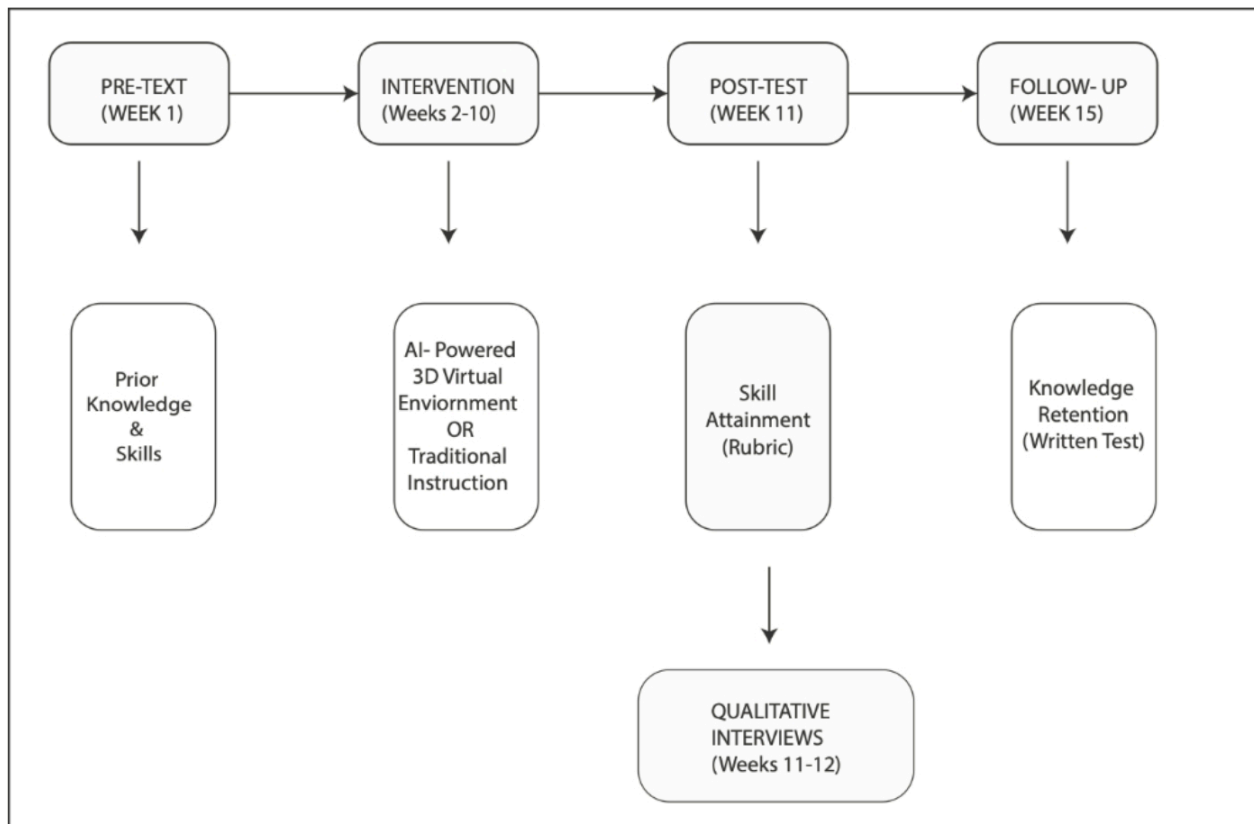


Figure 1

Data flow diagram of the research design

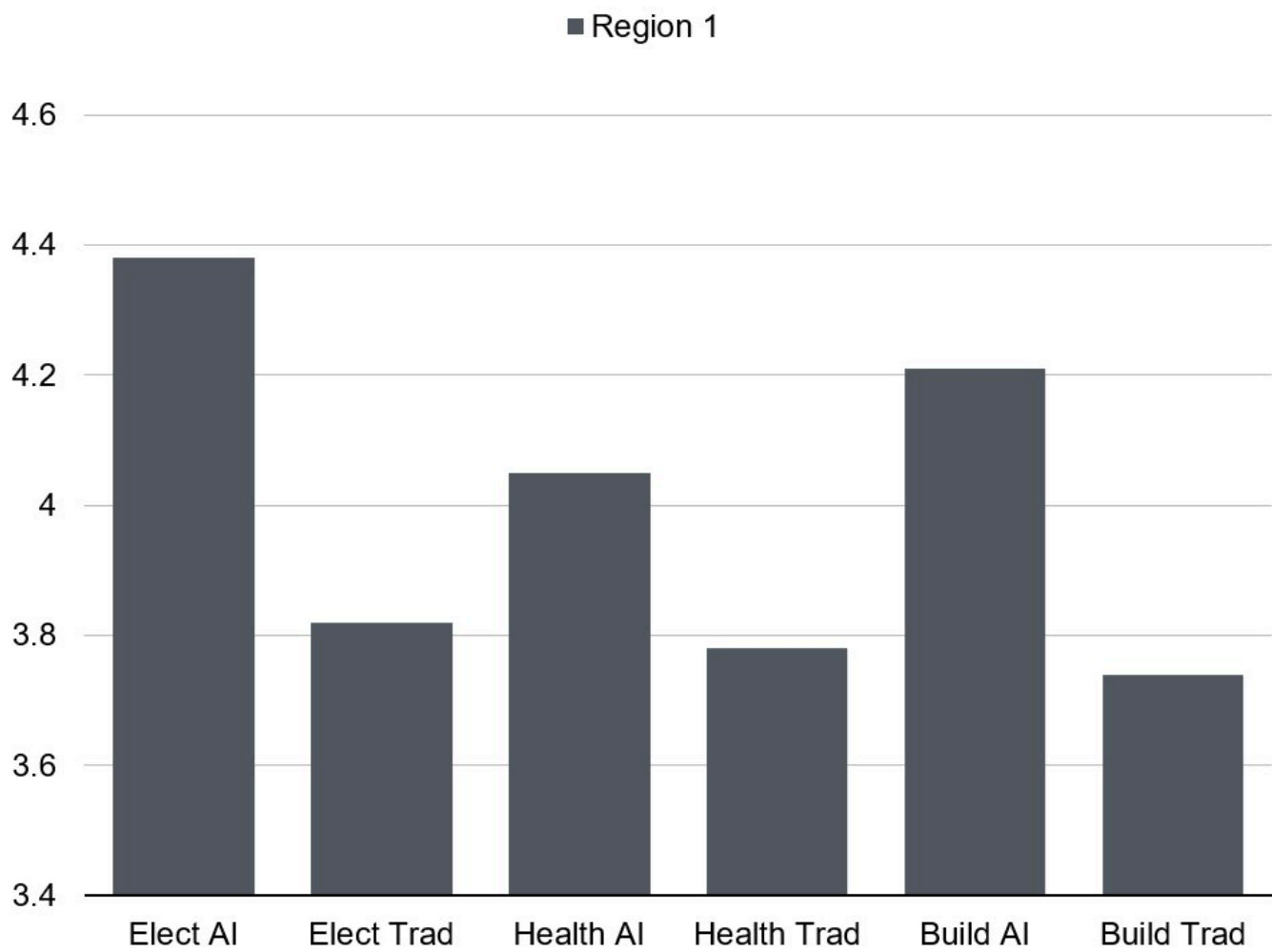


Figure 2

Skill attainment by condition and vocational field

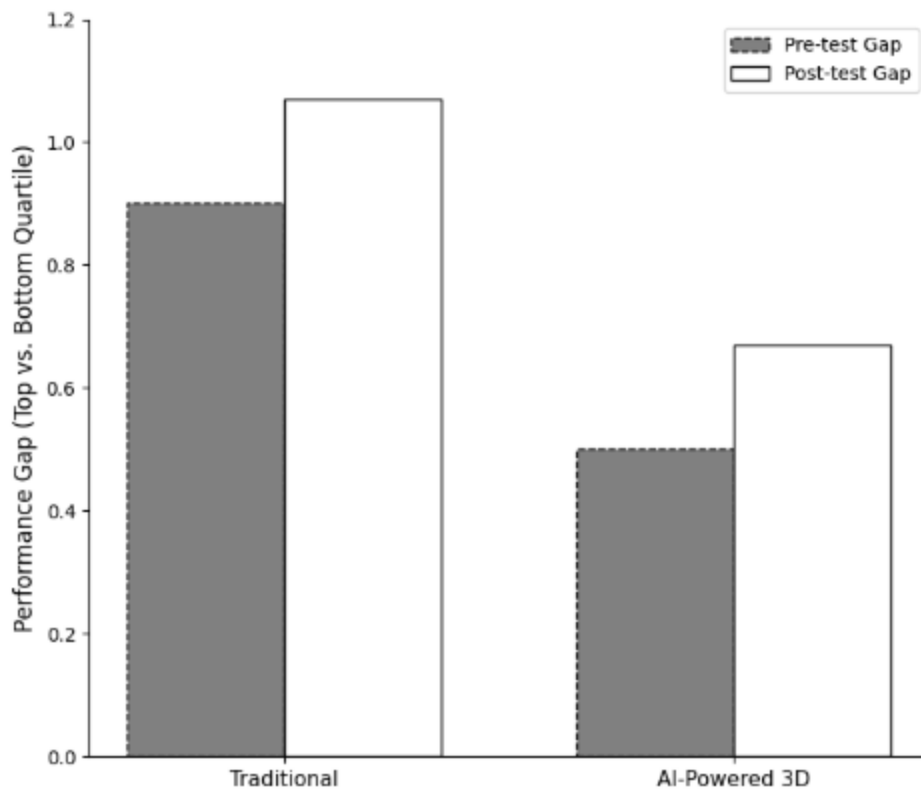


Figure 3

Performance gap reduction by pre-test quartile