AI-Enhanced Lesson Design within the TRinE 4D+ Pedagogical Model: Transforming Telepresence Robot-Mediated Education through Intelligent Systems

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Abstract

As educational institutions undergo rapid digital transformation, the integration of Telepresence Robots (TRs) and Artificial Intelligence (AI) offers new opportunities to make hybrid and distance learning more inclusive, personalised and engaging. Building on the validated "TRinE 4D Pedagogical Model" for Telepresence Robot (TR)-mediated education, this paper proposes the AI-Enhanced "TRinE 4D+ Pedagogical Model". The enhanced framework systematically embeds AI tools into each of the model's four phases: 1) Educational Context, 2) TR Settings, 3) Teaching Methods & Tools, and 3) Scenario & OER Design while preserving its Action Research foundation. The "TRinE 4D+ Pedagogical Model" implements adaptivity and differentiation through a three-phase methodological loop of a) *Pre-lesson Personalisation*, b) *In-lesson adaptivity* and c) *Post-lesson Reflective Redesign*, while maintaining teacher agency and an action-research foundation. To illustrate the model in practice, we present the "*TR Museum Quest: The Lost Myth of Athens"* scenario, a hybrid, TR-mediated language learning set of activities in which AI supports goal setting, TR configuration, adaptive serious games, and OER-based scenario documentation. The contribution of the paper is primarily conceptual and design-oriented: it provides a structured framework and concrete workflows for combining AI and mobile TR within a coherent pedagogical approach. Future pilots in schools, universities and museums will investigate the usability and impact of the "TRinE 4D+ Pedagogical Model" and inform further refinement of the model.

Keywords

Telepresence Robots, Distance Education, Distance Learning

1. Introduction

Over the past few years, hybrid and distance learning have become integral components of education. The COVID-19 pandemic forced a rapid transition to online and distance teaching, during which teachers had to develop their digital skills and adapt their practices under challenging conditions [1]. At the same time, many schools and universities have been pursuing broader digital transformation agendas that seek to integrate digital technologies more systematically into curricula, assessment and student support. Traditional videoconferencing tools offer basic remote participation but often fail to provide remote learners with a sense of presence, agency and social inclusion comparable to that of physically present peers [2]. Mobile Telepresence robots respond to this challenge by allowing remote participants to move within a physical space, approach peers and teachers, and focus on particular artefacts or parts of the environment, promising remote access to physical settings and a greater sense of presence than conventional virtual meetings [3]. As a result, Telepresence robots (TRs) have emerged as powerful tools for expanding access to education, particularly for learners unable to attend in person due to illness, distance or mobility issues. Prior work shows that TRs can foster a sense of "being there" and social participation for remote learners, providing a more realistic interaction than videoconferencing tools and making it less easy to "forget" remote learners [4]. Ahumada-Newhart and Olson [5]

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showed that children using the Vgo telepresence robot could maintain social connections and participate in class discussions during prolonged absence, highlighting the unique contribution of mobility and embodiment compared to static video links.

But how easy is it for teachers to design telepresence-robot (TR) scenarios, position the robots effectively in authentic learning spaces, and differentiate for diverse learners without any automated support? And how easy is it for students to use TRs confidently across different educational contexts and subjects? Within the context of the Erasmus+ KA2 project TRinE "Telepresence Robots in Education" (Ref.: 2020-1-MT01-KA227-SCH-092408), which examines how telepresence robots are utilised in educational settings at upper secondary and higher education levels, including classrooms and various online learning environments, Perifanou (2023) proposed the "TRinE 4D Pedagogical Model" [6] as a structured approach to designing telepresence-robot-mediated lessons. The model was iteratively refined and validated through a series of pilot studies carried out in five countries (Greece, Iceland, Malta, Germany and Austria) which explored different use cases, subject areas and organisational conditions for TR-mediated learning [6].

In parallel, AI-based tools in education have increasingly been used to support personalised learning, intelligent tutoring and learning analytics, offering new ways to tailor content, provide feedback and inform teaching decisions [7]–[10]. Recent work emphasises that such AI-driven personalisation should be aligned with established educational frameworks such as Bloom's taxonomy, the Common European Framework of Reference for Languages (CEFR) and Universal Design for Learning (UDL), in order to maintain pedagogical coherence and inclusivity [7], [11].

Responding to these needs, the aim of this paper is to explore how AI can be systematically integrated into the "TRinE 4D Pedagogical Model", resulting in the "AI-Enhanced TRinE 4D+ Pedagogical Model", which supports more personalised, adaptive and inclusive telepresence-robot teaching scenarios. The work is guided by three research questions. The first question asks how AI can enhance TR functionality and reliability in educational settings, addressing technical challenges. The second question examines how AI can adapt learning goals, content and paths to individual needs within TR-mediated lessons, addressing personalisation. The third question explores how AI and TRs can be combined in a pedagogical framework to support accessibility, diverse learning styles and equitable participation, addressing inclusion.

To address these questions, the paper first presents the theoretical background and the original "TRinE 4D Pedagogical model" [6]. It then outlines the methodology used to develop the 'TRinE 4D+ model", describes the AI-enhanced model and its workflow, and illustrates its application through the TR Museum Quest scenario. Finally, it briefly outlines planned evaluation and future empirical work, and points to implementation challenges and ethical issues for future pilots. This paper does not report empirical evaluation of the "TRinE 4D Pedagogical model"; instead, it focuses on the conceptual design of the model and show how it can be used through a concrete scenario, with empirical evaluation planned in forth coming pilots.

2. Background

2.1. Telepresence Robots in Education

Telepresence robots are mobile systems with videoconferencing capabilities that can be controlled remotely through a computer or mobile device. They typically comprise a motorised base, sensors, a screen, camera, microphone and speaker, and connect to the internet via wireless technologies [12]. The remote operator can navigate through an environment, observe activities from different viewpoints and interact with people in real time [3], [5]. The mobility of such robots is not merely a technical feature but fundamentally shapes the use cases and affordances of telepresence, distinguishing mobile robotic telepresence from static remote meeting tools [3].

In educational contexts, mobile telepresence robots have been used to enable students with longterm illness, physical disabilities or geographical constraints to attend school and participate in classroom life [5]. Ahumada-Newhart and Olson showed that children using the VGo telepresence robot could maintain social connections and participate in class discussions during prolonged absence [5]. The TRinE project has deployed telepresence robots across a range of educational settings, including remote students joining local classes, remote experts connecting to universities and cross-classroom collaborations, and has documented both inclusion benefits and pedagogical challenges [4], [6], [12].

Recent work in higher education has investigated telepresence robots as tools for remote participation in lectures, seminars and research activities, highlighting issues of trust, usability and the need for robust infrastructure [13], [14]. Using an extended technology acceptance model, Leietal showed that students' perceived usefulness, ease of use and social influence significantly shaped their acceptance of telepresence robots in higher education, underscoring that technical deployment must be accompanied by attention to attitudes and institutional context [14]. Studies in school environments have explored playful mobile telepresence with children, suggesting that robots can support engagement and participation but also introducing design considerations related to movement, safety and integration into classroom routines [15]. Design work on mobile telepresence has further emphasised that mobility shapes where and how robots can usefully be deployed, and has proposed a range of scenarios in which movement adds value beyond static videoconferencing [3].

These studies together emphasise both the inclusion potential of mobile telepresence robots and the importance of thoughtful pedagogical design, acceptance and organisational support. They also show that mobility and physical positioning of the robot, as well as the roles assigned to remote and local participants, are critical design parameters that must be considered explicitly. This insight is central for the "TRinE 4D Pedagogical Model" and its AI-enhanced extension.

2.2. AI for Adaptive and Inclusive Learning

AI has become an important component of many educational technologies. Machine learning and natural language processing techniques can be used to analyse learner behaviour, predict performance, generate personalised recommendations and provide automated feedback [7], [8]. Intelligent tutoring systems and adaptive learning platforms can adjust task difficulty and learning trajectories based on real-time data, while generative AI tools can help create content, examples and explanations tailored to different learners [9]. AI-empowered assessment systems have been shown to support online collaborative learning by providing personalised recommendations and feedback loops [9]. In higher education, AI-enabled personalised learning has been reported to improve engagement and academic performance in management education when integrated into course design [10].

There is also an increasing emphasis on using AI to support inclusion, for example through automatic captions and transcription, speech-to-text and text-to-speech tools, real-time translation and accessible interfaces. Work in Universal Design for Learning (UDL) argues that digital technologies, when designed appropriately, can provide multiple means of engagement, representation and expression that address learner variability [11]. Recent contributions have translated UDL principles into concrete strategies for inclusive instruction in higher education, emphasising flexible pathways, barrier removal and intentional design for diversity [11]. These principles inform the design of the "TRinE 4D+ Pedagogical Model" which emphasises an adaptive cycle of pre-lesson personalisation, in-lesson adaptivity and post-lesson reflective redesign (see Section 3.3).

Despite these advances, the integration of AI into hybrid and TR-mediated learning environments remains under-explored. In many cases AI is used as a separate component rather than being embedded in an overarching pedagogical model that structures how goals are defined, how scenarios are designed and how data are used for continuous improvement [8]. To our knowledge, existing work on telepresence robots and AI in education has not yet proposed an integrated pedagogical model that systematically combines AI-based adaptivity with mobile telepresence settings. The “TRinE 4D+ Pedagogical Model” addresses this gap by integrating AI capabilities systematically into a telepresence-robot pedagogical framework.

2.3. The “TRinE 4D Pedagogical Model”

The “TRinE 4D Pedagogical Model” [6] was developed in the context of the Erasmus+ KA2 project “TRinE – Telepresence Robots in Education” (Project Reference: 2020-1-MT01-KA227-SCH-092408) which explored the use of the telepresence robots (TRs) in educational institutions at upper secondary and higher education levels. The main aim was to design and propose a didactic framework that could facilitate the integration of TRs in education. The “TRinE 4D Pedagogical Model” [6], is grounded in the “Action Research” philosophy and methodology, following the iterative cycle of planning, acting, observing, and reflecting. It guides educators through four structured phases:

(1) Defining the Educational Context: analyzing learner profiles, curricular goals and institutional constraints.
(2) Describing the Educational TR Settings: configuring TR roles and interaction patterns (e.g., Remote Teacher → Local Class, Remote Student → Local Class, Remote Class → Local Expert).
(3) Selecting Teaching Methods and Tools: choosing appropriate pedagogical approaches such as collaborative learning, gamification or project-based learning and identifying suitable digital tools.
(4) Designing TR Teaching Scenarios as Open Educational Resources (OERs): developing shareable scenarios using a standard template, with an emphasis on collaboration, gamification and inclusivity.

Successfully piloted in several European institutions with 15 validated TR teaching scenarios, the model emphasizes collaboration, gamification, and inclusive pedagogy. However, in its original form, data use is limited and most adaptivity depends on teacher intuition and manual adjustments. Practitioners in the TRinE pilots expressed a need for more systematic, data-informed support, especially in complex hybrid situations where remote teachers, students, experts or whole classes participated via mobile telepresence robots and screen sharing, making it challenging to monitor everyone’s engagement. This is precisely where AI-enhanced extensions can strengthen the model.

3. The AI-Enhanced “TRinE 4D+ Pedagogical Model”

The AI-Enhanced “TRinE 4D+ Pedagogical Model” introduces AI as a cross-cutting layer that augments but does not replace the four original phases. It retains the Action Research logic while adding mechanisms for personalization, scalability and continuous optimization.

3.1. Overview

For The “TRinE 4D+ Pedagogical Model” (Fig.1) extends the original “TRinE 4D Pedagogical Model” [6] by integrating AI capabilities into each of its four phases. The structure of the model remains the same, but the activities within each phase are supported by AI in ways that aim to enhance personalisation, intelligent orchestration and data-informed reflection while preserving teacher agency.

Step 1: “AI-Supported Learning Goal Definition”: In the first phase, AI analyses students’ demographic profiles, prior performance data, such as previous assignments or language tests, as well as curricular descriptors to help educators define personalized learning goals and form effective groupings. It aligns learning objectives with established educational frameworks such as

CEFR and Bloom's taxonomy, supporting pedagogical decision-making while respecting teacher autonomy. The teacher reviews and adjusts these suggested goals, retaining full control.

Step 2: "AI-Guided TR Setting Selection": In the second phase, AI recommends the most appropriate TR configuration by analyzing the classroom's infrastructure, the learning goals, and physical context and resource constraints. It supports all six validated TR settings defined in the "TRinE 4D Pedagogical Model" [6]: (a) Remote Teacher ⟶Local Class, (b) Remote Expert ⟶ Local Class +Teacher, (c) Remote Student ⟶Local Teacher, (d) Remote Student ⟶ Local Student, (e) Remote Class ⟶ Local Teacher, (f) Remote Class ⟶ Local Expert or Local Class. In AI-enhanced TR settings, remote teachers and students are also supported by intelligent tools. For example, remote participants can: i) watch the video session with AI-generated captures or real-time translation; ii) receive an AI-generated transcript of the video interactions; iii) receive an AI-generated summary and highlighting key discussion points of the video session; iv) ask questions to an AI assistant for clarification of difficult concepts and receive answers, etc. Additionally, AI can simulate TR positioning and movement paths, optimize interaction flow, predict technical or accessibility issues, and recommend proactive solutions to ensure successful and inclusive deployment. This is particularly relevant in complex environments such as museums, where visibility, mobility and connectivity must all be considered [3], [4].

Step 3: "AI-Enhanced Teaching Methods and Tool Selection". In the third phase, AI can not only help educators select effective instructional strategies (e.g., collaborative learning, gamification, project based learning) but can also empower and enhance these methods through direct support. For example: a) In AI-powered collaborative learning, AI can automatically form student groups based on profiles or preferences, suggest group assignments, make adaptive recommendations, and evaluate collaborative outputs; b) In AI-supported serious games, AI can adjust difficulty levels or learning paths in real time; c) In AI-enhanced inquiry-based or project-based learning, AI can assist in question generation, resource curation, or feedback delivery. AI systems can also generate differentiated auxiliary content and formative assessment items that act as scaffolding within learning pathways [17] and drive real-time learning analytics dashboards that visualise learners' engagement to support timely instructional interventions [18].

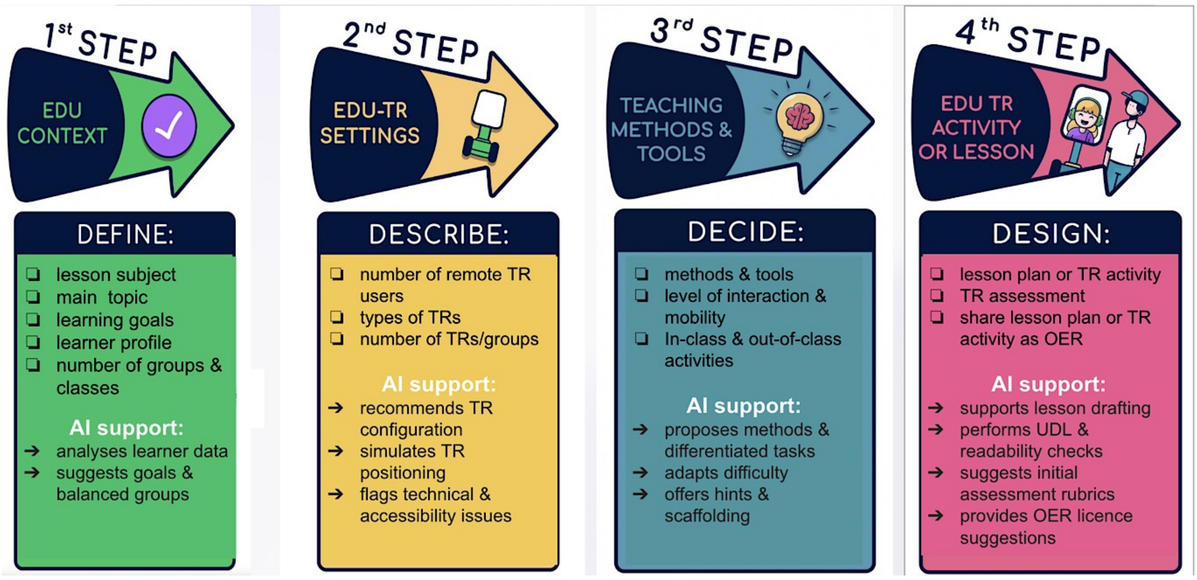

Figure 1: AI-Enhanced *"TRinE 4D+ Pedagogical Model"* with AI support across the four design steps

Step 4: "AI-Assisted Lesson Design and OER Development". In the fourth phase, AI can assist with the detailed design of the teaching scenario and with OER development. Educators can be guided in structuring teaching scenarios using the standardized TRinE OER template [6]. More concretely, AI systems can help teachers structure lesson plans in the TRinE template, check coherence between objectives, activities and assessment, and highlight potential accessibility issues, for example, in terms of language complexity or multimodal representation, in line with Universal Design for Learning (UDL) principles [11]. After the lesson, AI can also support the creation of OERs by suggesting licences, generating summaries and extracting key resources. The resulting scenarios can be published on the TRinE platform, promoting collaboration across a growing community of educators.

3.2. Comparison: TRinE 4D vs. TRinE 4D+

To make the relationship between the original "TRinE 4D" and "TRinE 4D+ Pedagogical Model" explicit, we include below a comparison table (Table 1), summarising the main differences and showing how each phase is augmented by AI support.

Table 1
TRinE 4D to TRinE 4D+ Pedagogical Model: core functions and AI augmentations

Phase	Original TRinE 4D focus	TRinE 4D+ AI enhancement
1. Educational Context	Manual analysis of learner profiles, curriculum and context; teacher-defined goals	AI analyzes performance data, prior assessments and learner preferences; proposes CEFR- and Bloom-aligned goals and balanced groups while teacher validates/edits
2. TR Settings	Selection among six validated TR configurations; manual consideration of room layout and constraints	AI recommends configurations based on goals, predicts technical/accessibility issues, simulates TR navigation and optimal positioning; suggests contingency plans
3. Methods & Tools	Teacher selects methods (collaborative learning, games, projects) and tools; limited dynamic adaptation	AI proposes methods aligned with goals and learner profiles; dynamically generates differentiated tasks, adapts difficulty in serious games, supports grouping and real-time scaffolding
4. Scenario & OER Design	Manual completion of TRinE scenario template; static OERs shared via TRinE platform	AI assists in drafting lesson plans, checking readability and UDL alignment, generating multimodal resources and initial assessment rubrics; facilitates versioning and reuse of OERs

This comparison shows that the "TRinE 4D+ Pedagogical Model" is not completely a new model but a systematic AI "overlay" on an already validated pedagogical framework. The "Action Research cycle" is preserved: data collected through AI-enhanced activities feeds back into subsequent iterations at all four phases. In each phase, AI acts as a decision-support tool: it generates suggestions and analytics, while teachers retain responsibility for all final pedagogical decisions. In the following, we describe how the "TRinE 4D+ Pedagogical Model" implements adaptive and differentiated learning across its phases.

3.3. Methodological Approach for Adaptive and Differentiated Learning

In response to the need for a clearer methodological and adaptive approach, "TRinE 4D+ Pedagogical Model" implements adaptivity and differentiation in three ways:

- **Pre-Lesson Personalization (Phase 1-2/ Plan: Educational Context & TR Settings):** Before the lesson, AI-supported analyses of learner data and curricular requirements help teachers establish differentiated objectives (e.g., focusing on descriptive vocabulary versus cultural analysis) and design group compositions (e.g., mixing proficiency levels or pairing remote students with supportive peers). In this phase, AI also guides TR setting selection, recommending one of the six validated TR configurations [6] and simulating TR positioning and movement paths to optimise visibility, interaction flow and accessibility in the specific physical environment (e.g., a classroom or museum).

- **In-Lesson Adaptivity (Phases 2–3/ Act & Observe: Methods &Tools):** During the lesson, AI monitors learner engagement and performance (e.g., success in QR-based tasks, participation in discussions, TR usage patterns) and can suggest micro-adjustments such as simplifying language, adding hints, proposing extension tasks for advanced learners or suggesting TR repositioning to increase visibility and interaction. In AI-enhanced TR settings, remote teachers and students are further supported by intelligent tools, such as AI generated captions or real-time translation, transcripts and summaries of key discussion points, and an AI assistant they can query for clarification of difficult concepts.
- **Post-Lesson Reflective Redesign (Phase 4 / Reflect: Scenario & OER Design):** After the lesson, AI-generated analytics and teacher reflections are combined to modify future iterations of the scenario: adjusting task sequences, revising difficulty levels and redesigning the roles of remote versus in-class students. These revisions are captured in the Scenario & OER Design phase and in updated versions of the TRinE scenario where the teacher also selects the preferred OER license (optionally supported by AI guidance).

This three-phase loop supports both individual adaptation and group-level differentiation, while maintaining teacher agency and preserving the pedagogical coherence of the "TRinE 4D Pedagogical Model". It is also consistent with the iterative logic of action research and design-based research as described by Hoadley & Campos [16].

4. Designing the TR Museum Quest: The Lost Myth of Athens" scenario

The "TR Museum Quest: The Lost Myth of Athens" scenario serves as an illustrative case of how TRinE 4D+ can be instantiated in practice. The scenario is designed for English language learners at B2–C1 level who visit a museum in Athens, or a simulated equivalent, and collaborate to reconstruct a "lost myth" by exploring exhibits, scanning QR codes and completing language and culture tasks. It was authored using the TRinE scenario template developed by Perifanou [6].

The educational context is defined by parameters such as subject area, topic, learner profile and target skills. The subject area is English as a foreign language, with a strong component of cultural and historical awareness. The main topic is Greek mythology and its representation in artefacts. The target group consists of university students, some of whom are physically present in the museum while at least one student participates remotely through a mobile telepresence robot. Learning goals include developing descriptive and narrative skills in English, practising critical thinking about cultural heritage and practising collaboration in hybrid teams. In terms of TR settings, the scenario adopts a configuration where a remote student controls a mobile telepresence robot that moves through the museum alongside local classmates. The remote student can approach exhibits, scan QR codes and contribute to decision-making. Local students support navigation, engage with museum staff and handle physical materials where needed. Group sizes are defined so that each telepresence robot is shared by a small team, enabling meaningful interaction. This configuration draws on existing work [5], [13], that shows how mobile telepresence can support both participation and social presence in schooling and higher education, as well as research on playful engagement in classroom and informal settings [15].

AI support appears at several points in the scenario. During preparation, the system can analyse available learner data to suggest differentiated language goals and propose balanced groupings that mix different proficiency levels and digital skills. Before the visit, the teacher can use AI-generated suggestions to refine objectives and design pre-visit activities that activate prior knowledge and introduce key vocabulary.

During the museum visit, AI-enhanced serious games come into play. QR codes associated with selected artefacts lead to tasks whose difficulty and focus are adapted to the learners' profiles. For some students, the prompts emphasise vocabulary and description, while for others they focus on comparison, interpretation or argumentation. As learners respond, the system can provide hints, alternative explanations or additional examples when difficulties are detected. When teams progress quickly, more challenging extension tasks can be proposed. The use of playful, quest-based tasks builds on evidence that mobile TR can support engagement and playful participation for young people [15].

AI can also support language production directly, for instance, by offering vocabulary suggestions or proposing alternative phrasings that learners can accept or adapt, particularly at the drafting stage. This is done with the teacher's awareness and guidance, in order to avoid over-reliance on automated suggestions and to maintain the authenticity of student work.

After the visit, AI assistance continues in the reflection and production phase. AI tools can help students to organise their notes and media, to draft and revise their reconstructed myth of Athens, and to create multimodal artefacts such as digital posters or short videos. At the same time, it can help the teacher to generate initial rubrics for assessing language, collaboration and cultural understanding, and to produce a first draft of the scenario documentation as an OER, which the teacher then edits. The final scenario, including variations for different levels and contexts, can be shared on the TRinE platform.

5. Conclusion and Future Work

This paper has introduced the AI-Enhanced "TRinE 4D+ Pedagogical Model", which extends a previously validated framework for TR-mediated education by integrating AI support into each phase of lesson design and implementation. The proposed model maintains the structural strengths of the original "TRinE 4D Pedagogical Model" [6], including its Action Research underpinning and its emphasis on collaboration, gamification and scenario sharing, while adding mechanisms for personalisation, intelligent orchestration and data-informed refinement in line with work on AI in education [7], [8], [10].

We described the methodological foundations of "TRinE 4D+ Pedagogical Model", highlighting how action research and design-based research, as discussed by Hoadley and Campos [16], inform an iterative cycle of design, enactment, analysis and redesign. The "TR Museum Quest: The Lost Myth of Athens" scenario was presented as a design exemplar that showcases how AI support can be embedded in a concrete telepresence-robot-mediated learning activity, from AI-assisted goal setting and TR configuration, through AI-enhanced serious games during a museum visit, to AI supported reflection and OER creation.

The current work remains conceptual and exploratory and provides a structured basis for future empirical investigation. Planned pilots in schools, universities and museums will be used to test and refine the model, to investigate learner and teacher experiences and to examine conditions for successful integration of AI and telepresence robots in educational practice, including organisational and ethical aspects. For practitioners, TRinE 4D+ offers a structured workflow and scenario template to plan AI-enhanced telepresence lessons while retaining teacher control. For institutions, the model highlights the need for professional development around AI-augmented TR teaching and for organisational support for scenario sharing and OER reuse. However, implementing the "TRinE 4D+ Pedagogical Model" also raises practical considerations: schools and universities will need reliable connectivity, adequate access to mobile telepresence robots and appropriate teacher training so that AI suggestions are interpreted critically rather than followed blindly. From an ethical perspective, the use of learner data for personalisation requires transparency, informed consent and attention to data protection and academic integrity, particularly when AI tools support language production.

Future research will focus on implementing "TRinE 4D+ Pedagogical Model" in real-world settings, developing teacher professional development pathways around AI-augmented telepresence teaching and expanding the TRinE scenario library with AI-enhanced OERs co-created by practitioners. In this way, the "TRinE 4D+ Pedagogical Model" aims to move TR-mediated education from isolated pilots to sustainable, inclusive and adaptive practices that exploit both telepresence robots and AI within a robust pedagogical framework.

Declaration on Generative AI

During the preparation of this work, the author used *Grammarly* for grammar and spelling check. The author reviewed and edited the content as needed and take full responsibility for the publication's content.

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