DOCTORAL THESIS

Integrating Telepresence Robots into the Teaching and Learning Process

Tiina Kasuk

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Declaration:
I hereby declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for a doctoral or equivalent academic degree at any other university or institution.

Tiina Kasuk

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Contents

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Other related publications

The author has contributed to other publications during her studies at Tallinn University of Technology:

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V Kasuk, T., Leoste, J., Savova, A., Anđić, B., & Fenyvesi, K. (2025). Design and pilot implementation of telepresence robots in higher education courses. In M. E. Auer & T. Rüütmann (Eds.), *Futureproofing Engineering Education for Global Responsibility*, 253–264. Springer, Cham. https://doi.org/10.1007/978-3-031-83520-9_25

VI Kasuk, T., Leoste, J., Meeran, M. T., Talisainen, A., & Budagov, F. (2025). Telepresence robots and inclusive hybrid learning: Bridging gaps in higher education classrooms. In R. Balogh, D. Obdržálek, & N. Fachantidis (Eds.), *Robotics in Education*, 498–507. Springer, Cham. https://doi.org/10.1007/978-3-031-98762-5_42

VII Leoste, J., Kasuk, T., Marmor, K., & Käver, A. (2025). Evaluating multi-user telepresence robot interaction in cybersecurity education. *2025 IEEE Conference on Telepresence*, 15–20. https://doi.org/10.1109/Telepresence66096.2025.11521717

VIII Kasuk, T., Leoste, J., Rakic, S., & Banko, A. (in press). Evolving student perceptions of teaching via a telepresence robot: A comparative study. *Robotics in Education Conference 2026*.

Author’s Contributions to the Publications

Contributions to the papers included in this thesis are:

I In this article, I was the lead author. I designed and executed the structured literature search and screening, compiled the dataset, and conducted the bibliometric mapping and thematic synthesis reported in the paper. I produced the analytical figures and tables and drafted the full manuscript. I also managed the revision process, addressing methodological and interpretive comments from my supervisors and the journal’s reviewers.

II In this article, I was the lead author. I co-designed the three qualitative studies, coordinated data collection (course piloting and teacher workshop), curated and analysed the data, and led the development and visualisation of the PEPCII pedagogical design model. I wrote the original draft, integrated co-author feedback, and oversaw submission. The published article’s author-contribution statement confirms my roles in conceptualisation, methodology, data curation, investigation, formal analysis, project administration, visualisation, and writing; co-authors contributed supervision, validation, and critical revision.

III In this manuscript, I was the lead author. I designed the validation study aligned to the PEPCII dimensions, developed the research instruments, coordinated data collection, and conducted the analysis. I drafted the manuscript, prepared figures and tables, and integrated co-author feedback. Co-authors contributed to study design refinement, methodological validation, and critical revision of the text.

Other related publications

Contributions to the papers included in this thesis are:

IV In this chapter, I was the lead author. I defined the scope of the contribution, designed the three pilot studies (teacher interviews, a 13-week TPR-mediated course, and 13 hands-on workshops), coordinated data collection, and led the thematic analysis that shaped the final checklist-style pedagogical guidelines. I drafted the manuscript, prepared the figures and tables, and integrated co-author and editor feedback through revision rounds.

V I was the lead author. I developed the inclusive hybrid learning framing for TPR use, compiled case-based evidence from higher-education classrooms, and synthesised practical design implications. I drafted the manuscript, prepared figures and tables, and coordinated co-author input during revisions.

VI In this chapter, I was the lead author. I developed the inclusive hybrid learning framing for TPR use, compiled case-based evidence from higher-education classrooms, and synthesised practical design implications. I drafted the manuscript text, prepared figures and tables, and coordinated co-author input during revisions.

VII In this conference manuscript, I was a co-author. I contributed to study design on multi-user and shared-embodiment TPR operation in a cybersecurity class, helped develop the mixed-methods instruments (Likert-scale items and open questions), and supported data collection. I co-wrote the Results and Discussion sections. I assisted in preparing figures and tables for the manuscript.

VIII I was the lead author. I led the design study and organised the data collection. I wrote the draft of the manuscript, analysed data, prepared figures and tables, and coordinated the contributions of the co-authors during editing.

Introduction

For several decades, educational researchers have systematically examined diverse pedagogical methodologies designed to augment remote student engagement, thereby expanding the parameters of educational accessibility. If we look at the history of education, we see that widely available education has developed under the influence of innovative solutions and ideas. In the pre-industrial era, accessibility to education varied across different social classes and countries. In the Middle Ages, schools established at monasteries and guilds provided access to education only to a narrow and rather elite class of society. However, education remained inaccessible to the lower classes of society (Eskelson, 2021). Primary education was first made compulsory in Prussia in 1763 to ensure a uniform preparation of the population (Green, 2013).

The first industrial revolution created a need for a workforce who could read, write, calculate, and understand work procedures. The acquisition of professional knowledge moved from the apprentice model to engineering and vocational schools (Crawley et al., 2014). After World War II, education underwent several reforms, with the aim of ensuring access to education, including higher education, and developing the economy (Schofer & Meyer, 2005). Learning from experience began to be valued, and engineering education emerged as a discipline (Crawley et al., 2014). Education, especially higher education, remained difficult to access for students from lower socioeconomic backgrounds (Osler, 2024).

The origins of distance education are commonly traced to correspondence-based instruction in the eighteenth century. Early forms of distance learning relied on postal services to distribute learning materials and feedback to geographically dispersed learners (Kentnor, 2015). During the nineteenth and twentieth centuries, distance education expanded through correspondence courses, institutional programmes, and later radio and television broadcasting, significantly increasing educational access beyond traditional classroom settings (B. Anderson & Simpson, 2024; Huffman et al., 2011).

With the advent of global networking, characterised by the widespread accessibility of the internet and personal computing devices, educational institutions rapidly integrated advanced technological systems to enhance educational delivery. This development transformed distance education from predominantly one-way modes of content delivery into interactive learning environments, enabling communication and collaboration among students, educators, and peers (T. Anderson & Dron, 2011). This paradigm change enabled students to engage in knowledge construction, drawing upon pre-existing cognitive frameworks and experiential learning, as well as through collaborative interactions with educators and peers.

The term Digital Education has been developed along with the development of technological tools. Its modern meanings have been described by (Fawns, 2019). From the 1960s to the 1980s, education actively adopted computer-assisted instruction (CAI), where computers mediated instructions for students, supporting both the acquisition of new material as well as practice and repetition (Fitzgerald et al., 2008). Following the adoption of computer-assisted instruction, the invention of the World Wide Web (WWW) further enhanced access to study materials through web browsers. The creation of the WWW laid the foundation for online learning, where various web-based platforms began to host e-learning courses and organise knowledge acquisition (Harasim, 2000).

By the advent of the 21st century, notwithstanding the proliferation of web-based learning modalities, the utilisation of traditional textbooks remained widespread. However, for students from lower socioeconomic backgrounds, these resources frequently proved to be financially prohibitive. The initiative aimed at democratising access to educational resources, irrespective of financial imitations, served as a catalyst for the emergence of the Open Education Resources (OER) movement. This movement was characterised by the proactive dissemination of academic materials by prestigious universities (Hilton, 2020).

The continued development of web-based technologies and increasing internet speeds enabled the delivery of learning content through recorded videos or live streaming. This created the possibility of obtaining education entirely through e-learning courses. Fully online learning offers greater flexibility, increased opportunities for reflection, and broader participation, as learning may take place asynchronously, synchronously, or through a combination of both approaches (Hrastinski, 2008; Raes et al., 2020).

Although online learning substantially improved educational accessibility, it often reduced opportunities for social interaction, immediacy, and a sense of belonging (Lomellini et al., 2025). In comparison with face-to-face learning, online students may experience social isolation, technical difficulties, delayed feedback, and a greater need for self-regulation and motivation (Kebritchi et al., 2017; Kemp & Grieve, 2014).These limitations contributed to the emergence of hybrid and synchronous hybrid learning models that combine the flexibility of online participation with the social benefits of face-to-face learning (Bell et al., 2014; Raes et al., 2020).

The restrictions on learning brought by the COVID-19 pandemic accelerated the development of technological solutions, such as video conferencing, which became integral to the blended learning approach. Yet, students participating remotely continued to struggle with feelings of loneliness and separation from classmates (Fabian et al., 2024). Emerging technologies such as telepresence robots (TPRs) enable students to overcome these limitations and have a more active participation in the educational process (Ahumada-Newhart & Olson, 2019; Page et al., 2021). These students have a better learning motivation when supported by the robot because they have a sense of independence as well as belonging in the classroom ((Nordtug & Johannessen, 2023; Powell et al., 2021).

The current doctoral thesis explores the role of TPRs in synchronous hybrid learning in relation to key United Nations sustainable development goals (United Nations Development Programme, n.d.), particularly quality education (SDG 4), reduced inequalities (SDG 10), and good health and well-being (SDG 3). This aligns with the United Nations' call for evidence-based acceleration in education, digital connectivity, and inclusive development. International policy frameworks identify education as a key domain through which multiple sustainable development goals can be advanced, particularly where digital innovation and inclusion intersect. Synchronous hybrid learning offers educational and social benefits, including improved access for remote students, increased flexibility, and opportunities for sustained participation in learning activities (Bell et al., 2014; Fabian et al., 2024; OECD et al., 2022). In the post-COVID era, digital and hybrid forms of learning have gained particular importance, as the pandemic highlighted the need for resilient education systems capable of adapting to disruptions through the effective use of technology (OECD et al., 2022). The integration of inclusive pedagogy, responsible digital innovation, and sustainable educational practices reflects a broader shift towards transforming education systems rather than merely adopting new technologies (Rajasekaran et al., 2024).

Synchronous hybrid learning enabled by TPRs represents one possible response to the United Nations’ call to strengthen education systems in a fair, scalable, and context-sensitive manner while enabling meaningful digital learning pathways (Rajasekaran et al., 2024). TPRs support quality education (SDG 4) by providing schools, teachers, and students with pedagogically grounded frameworks and practical guidelines for the effective implementation of digital technologies in learning environments. Such support can help address challenges repeatedly identified in international research concerning the meaningful integration of technology into education (Global Education Monitoring Report Team, 2024). In addition, TPR use in hybrid learning may contribute to reducing inequalities (SDG 10) by enabling participation for students who face barriers to attendance due to health conditions, special educational needs, anxiety, or geographical distance. This aligns with international human rights frameworks that emphasise the right to inclusive and accessible education for vulnerable students (UNESCO & Right to Education Initiative, 2019).

Given the importance of social belonging and peer interaction for students separated from their classroom community (OECD et al., 2022), TPRs can support continued participation in educational and social activities, helping to reduce isolation and promoting psychosocial well-being. In this respect, TPR-mediated participation aligns with the objectives of SDG 3 (good health and well-being). International education recovery frameworks increasingly stress that student well-being, social cohesion, and psychosocial support are integral components of quality education and long-term learning outcomes (OECD et al., 2022).

TPRs may contribute to SDG 13 (climate action) by reducing travel requirements associated with educational participation and supporting more resilient forms of hybrid learning. While the environmental impacts of TPR-mediated learning were not directly examined in this study, hybrid participation models have the potential to reduce the need for physical travel and thereby support more sustainable educational practices. Furthermore, the development and validation of the PEPCII pedagogical design model contributes to SDG 9 (industry, innovation, and infrastructure), particularly through advancing innovation in technology-enhanced learning and highlighting the technical and organisational conditions necessary for the sustainable implementation of telepresence technologies in education. This aligns with international recommendations to strengthen the digital infrastructure of education and to enhance the innovation capacity and resilience of educational systems (Rajasekaran et al., 2024).

Problem Statement

Rapid development of digital technologies creates opportunities for more flexible learning compared to previous pedagogical practices. Hybrid and online learning offer the possibility to participate in the learning process remotely. However, they do not enable remote students to have immediate interaction, physical, and social presence, which are characteristic of face-to-face learning. As a result, remote students often feel socially isolated from their classmates due to the lack of physical and social presence.

TPRs help to overcome the limitations of hybrid and online learning by enabling remote students to participate physically and socially in the learning environment through an embodied, mobile presence, which simulates the experience of being in a physical classroom.

Despite the opportunities offered by TPRs, their use in education today remains limited due to the lack of strategies and pedagogical guidelines necessary for effective implementation. Existing implementations of TPRs have often focused on technical feasibility, overlooking essential educational aspects, including curriculum integration, ethical considerations such as privacy, and organizational dimensions such as institutional support, which are crucial for their effective use. The broader adoption of telepresence technologies is hindered by the absence of well-defined institutional frameworks, including policies, support systems, and best practices for implementation, as well as the limited accessibility of technology.

This doctoral thesis addresses the following main research question (RQ):

What framework can guide the integration of telepresence robots in synchronous hybrid learning environments?

This overarching inquiry is addressed through the following sub-research questions (SRQ):

- SRQ1 What are the main pedagogical opportunities and challenges identified in existing research on integrating telepresence robots into educational settings?
- SRQ2 How can a pedagogical design model be developed to support the effective and inclusive integration of telepresence robots in synchronous hybrid learning?
- SRQ3 How does the implementation of the PEPCII pedagogical design model demonstrate its practical applicability in supporting engagement, inclusion, and pedagogical alignment in higher education settings using telepresence robots?

By addressing these questions, this thesis seeks to close the divide between technological potential and pedagogical practice. Its goal is to promote a theoretically grounded and empirically validated framework that supports teachers and institutions in designing inclusive, interactive, and sustainable hybrid learning environments through the purposeful integration of TPRs.

The concept of pedagogical design in this thesis refers to the intentional design of learning environments, communication processes, and student engagement practices that support the active participation of remote students in synchronous hybrid learning. Within this study, pedagogical design extends beyond curriculum and instructional design to include the broader pedagogical, technological, and organisational conditions that influence participation, interaction, inclusion, and engagement in TPR-mediated learning environments.

Research Contributions and Significance

This thesis explores how TPRs can be integrated into synchronous hybrid learning environments to create more inclusive educational opportunities for remote students. The study focuses on enhancing participation, social presence, and well-being for all participants, including TPR-mediated students, in-class students, and teachers.

The main outcome of the research is a validated pedagogical design model accompanied by a practical instructional guide for implementing TPRs in educational settings. Together, these outputs address a significant gap in existing research and practice: while TPRs have demonstrated potential to enhance engagement, interaction, and inclusion, there remains a lack of pedagogically grounded frameworks to support their systematic implementation in teaching and learning.

Rather than viewing TPR integration as a purely technological challenge, this thesis approaches it as a pedagogical design problem. The proposed solution emphasises the alignment of pedagogical, technological, organisational, and disciplinary considerations to support meaningful participation and inclusive learning experiences. Consequently, the thesis positions TPR use in learning as a multidimensional design challenge, encompassing didactic, socio-emotional, spatial, and technological dimensions.

Structure of the Thesis

The thesis is organised into five chapters, including this introductory Chapter 1. Chapter 2 presents the theoretical background. Chapter 3 presents the methodological framework, outlining the design-thinking approach and research methods used to develop and refine the PEPCII model for TPR-enabled hybrid learning. Chapter 4 summarises the empirical studies, describing the design, implementation, and validation of the model through case studies and multi-stakeholder workshops. Chapter 5 discusses the main findings in relation to existing literature, highlighting theoretical, pedagogical, and practical implications, as well as the study's limitations and areas for future research. Finally, Chapter 6 concludes the thesis by summarising the key contributions, addressing the research questions, and reflecting on how the findings advance inclusive, sustainable, and technology-enhanced learning in higher education.

1 Theoretical Background

1.1 Technological Foundations of Telepresence Robots

Minsky's (1980) concept 'telepresence' marked a significant technological advancement, allowing individuals to experience distant environments and laying the groundwork for modern remote communication technologies. He combined earlier notions such as 'teleoperate', which refers to remote operation, and 'telefactor', which involves remote manipulation. Minsky considered high-quality sensor feedback important, as it enables, through technology, the embodiment of oneself in another location. Edwards (2011) expanded on telepresence by emphasising its ability to simulate a shared physical space for all communication partners. The prerequisite for this is high-quality video and audio, as well as the transmission and reproduction of gestures and nonverbal signals, which create the conditions for social and bodily presence. These principles form the basis for today's TPRs. These conceptual foundations later enabled the development of embodied telepresence systems such as TPRs. Originally, the possible areas of use for telepresence were seen as places where it is dangerous for a person to be, such as nuclear power plants and mines (Ijsselsteijn, 2005). Later, this expanded into medicine (Takács et al., 2016), from which the first TPRs developed. With the emergence of videoconferencing systems and the development of commercial TPRs, telepresence also spread into education, social interaction, and health care (Kristoffersson et al., 2013; Newhart et al., 2016; Tsui et al., 2011).

TPRs are videoconferencing systems on wheels that provide a physical representation for a remote person and support their social presence (Tsui et al., 2011). They are complete mobile platforms that enable social interaction with people present in the room (Kristoffersson et al., 2013). The main advantage over standard videoconferencing solutions is the robot's autonomy, which allows users to navigate the space freely, thereby enhancing interaction and engagement (Tsui et al., 2011). A TPR enriches typical videoconference communication by allowing movement in the room and a more natural turn-taking in conversation (Herring, 2013). The experience of using a TPR is influenced by simple user interfaces and cognitive load (Lei et al., 2022). A TPR is not an autonomous humanoid robot. Instead, it is an integrated system controlled by the user via an internet connection, consisting of a camera, microphone, speakers, screen, mobility platform, and sensors (Kristoffersson et al., 2013).

Remote participants achieve a sense of presence when they can actively engage in activities and receive social cues as if they were physically in the room (Boudouraki et al., 2023). Minsky emphasised that users must be enabled to act at a distance 'as though in person'. A TPR allows the user to operate as an agent within the physical space through the robot, thereby experiencing the process of embodiment (Boudouraki et al., 2023). The robot's technical characteristics influence social presence, agency, and may raise or lower cognitive load during TPR use. The camera's field of view affects situational awareness and the perception of body language. Social interaction is also influenced by microphone's directionality (Tsui et al., 2011) and by the screen's position and height (Ahumada-Newhart & Olson, 2019). Participating in a class via TPR increases cognitive load (Elmimouni & Sabanovic, 2025). However, autonomous navigation can reduce this load by allowing the user to focus more on the class content, which in turn improves performance on working-memory tasks by freeing the user's attention from other signals

(Pan et al., 2024). These studies suggest that technical design choices directly shape the quality of social presence and cognitive load in TPR use.

1.2 Telepresence Robots in Education

TPRs are transforming educational engagement, offering new opportunities for students and teachers, especially those hindered by injuries, chronic illnesses, or geographical barriers.

TPRs not only facilitate classroom participation for homebound students by providing real-time interaction with peers and teachers but also enable them to engage in meaningful educational activities, such as collaborative projects and virtual field trips (Hu et al., 2024; Page et al., 2021). Through the use of TPRs, opportunities arise for social interaction – students can engage in extracurricular activities, such as field trips, which are crucial for their holistic development (Ahumada-Newhart & Olson, 2019; Nordtug & Johannessen, 2023; Spoden & Ema, 2024). Extended periods away from the classroom can still foster friendships through the interactive communication capabilities of TPRs (Powell et al., 2021).

Gradual reintegration into learning with TPRs helps reduce school-related anxiety in homebound children (Weibel et al., 2023) and supports the maintenance of social connections while helping to prevent loneliness (Nordtug & Johannessen, 2023). Participating in learning through a TPR helps children who are in isolation improve their mood and strengthen their sense of belonging (Powell et al., 2021). In addition, it can support students with an autism spectrum disorder in learning participation (Spoden & Ema, 2024). Using TPRs for observation allows teachers and mental health professionals to assess children's mental health by monitoring their interactions and emotional responses in a controlled environment (Jent et al., 2024).

Using TPRs in synchronous hybrid learning, where some students are physically present and others participate remotely, enables a more inclusive learning experience (Capello et al., 2022). Additionally, TPRs open opportunities for more authentic learning experiences, such as allowing medical and nursing students to learn in real-world environments and enabling group work across different locations, thereby enhancing collaborative skills and practical knowledge (Huun & Slaven, 2024; Naseer et al., 2023). Furthermore, this approach enables students to receive immediate feedback from their mentors or instructors during the learning process (Mudd et al., 2020). Also, TPRs can enable expanded access to science conferences without expense and time of travel (Lueg et al., 2020). In language learning, TPRs allow native speakers to be brought into the classroom (Yun et al., 2013) and create more realistic communication situations to support language learning in out-of-class environments (Liao et al., 2022). They also make education more accessible to students in remote regions (Jakonen & Jauni, 2022).

Although TPRs are primarily used by students, there are significant benefits also for teachers. Teachers can conduct lessons through TPRs when unable to be physically present, offering a more interactive and engaging alternative to traditional videoconferencing (Kim et al., 2025). This capability allows teachers to maintain a dynamic presence in the classroom, thereby fostering a more connected and responsive educational environment by actively engaging with students and adapting to their needs in real-time. This applies both to conducting workshops (Okundaye et al., 2020) and to physical education classes (Puarungroj & Boonsirisumpun, 2020). TPRs can extend the presence of instructors or experts in the classroom (Häfner et al., 2023) or involve older adults to share their experience (Okamura & Tanaka, 2016). Their use enables flexible involvement of experts in lessons and environmental assessments (Lu & Nishimura, 2024). Furthermore, TPRs could help teacher training students develop their teaching skills during their studies, enabling them to conduct lessons in a real classroom (Basque et al., 2025).

1.3 Technology Adoption Models for Adopting Telepresence Robots in Education

TPR technology fundamentally alters the learning process by allowing remote students to participate as if they were physically present (Fitter et al., 2020; Kim et al., 2025). This transformation challenges traditional notions of presence by necessitating changes in classroom layouts, communication methods, and student-teacher interactions (Hordemann et al., 2024; Mäntyoja & Hautala, 2025), as well school infrastructure (Newhart & Olson, 2017). TPR redefines the teacher's professional role by integrating technology that supports learning and requiring adaptations to classroom management practices (Jakonen & Jauni, 2022; Weibel et al., 2024), while simultaneously introducing responsibilities for maintaining a safe learning environment (Capello et al., 2022; Neumann et al., 2025). Additionally, training users and building support and booking systems is necessary (Powell et al., 2021; Spoden & Ema, 2024). To effectively implement TPRs, educators can rely on specific technology adoption models and educational technology frameworks, which will be explored in the following chapters (Han & Conti, 2020; Huun & Slaven, 2024).

The Technology Acceptance Model (TAM) is often used as a basis for adopting new technology. TAM predicts users' decisions to adopt new information technologies (Davis & Granić, 2024). In his original description of TAM, Davis (1989) argued that the adoption of a new technological tool is shaped by the user's perceived usefulness (PU) and ease of use (PEOU). In the extended TAM 2 by Venkatesh & Davis (2000), additional external determinants substantially influence the likelihood of technology adoption. These include social influence processes (subjective norm, voluntariness, and image) and cognitive instrumental processes (job relevance, output quality, result demonstrability, and perceived ease of use). The willingness to adapt to new technology is also influenced by factors such as experience with technology and the level of voluntariness in its adoption. (Venkatesh & Bala, 2008). Addressing this gap requires developing clear guidelines and training programmes to equip educators with necessary skills (Scherer et al., 2019).

The Unified Theory of Acceptance and Use of Technology (UTAUT), developed by Venkatesh et al. (2003), was designed to acquire a deeper understanding of users' technology adoption and to predict their behaviour. UTAUT was created in response to the excessive fragmentation of earlier models and theories regarding technology acceptance, aiming to establish a unified model. Its primary constructs are Performance Expectancy (PE), Effort Expectancy (EE), Social Influence (SI), and Facilitating Conditions (FC), focusing on users' levels of technology adoption. A meta-analysis by (Khechine et al., 2016) highlights UTAUT's application for webinars, mobile learning, and other blended learning solutions in education.

Mishra & Koehler (2006) developed the Technological Pedagogical Content Knowledge (TPACK) framework for educators and researchers. It helps to analyse how teachers are prepared to adopt or use new technology, pedagogy, and content to enhance learning. There are three main components (knowledge domains) of teachers:

CK (content knowledge), PK (pedagogical knowledge), and TK (technology knowledge). The interactions between and among these primary components are TCK (technological content knowledge), TPK (technological pedagogical knowledge), and TPACK (technological pedagogical content knowledge). When implementing emerging technologies into education, TPACK guides teachers in designing technology-enhanced learning experiences that align with content goals and pedagogical approaches. TPACK is often criticised for being too broad in scope, which can dilute its applicability. For example, educators may struggle to focus on specific subject areas or technologies, leading to less effective integration strategies. Focusing on subjects could enhance its utility by providing more targeted guidance for educators. The clear focus has led to the emergence of various new versions of TPACK, designed to support the use of specific technologies in different subject areas (Brantley-Dias & Ertmer, 2013). It is considered as a framework that is not directly a tool that teachers can independently use to integrate emerging technologies into their teaching. Over the years, tools have been developed from TPACK to support teachers' self-reflection (Voogt et al., 2013). In the context of this thesis, TPACK guides the development of a pedagogical design model that equally considers learning content, teaching methods, and pedagogical knowledge to implement TPACK technology in the learning process.

To describe and analyse students' cognitive engagement in learning activities, Chi & Wylie (2014) developed the ICAP framework (Interactive–Constructive–Active–Passive), which distinguishes four modes of engagement: passive (the student receives information without directly doing anything with it), active (the student manipulates or practices existing information), constructive (the student creates new knowledge, e.g. explains, connects, or infers), and interactive (the student creates new knowledge through collaboration and dialogue). Each higher-level mode is more likely to ensure deeper learning. New technology often leaves students in a passive mode (Anđić et al., 2025). To evaluate teachers' adoption of technology, a framework-based instrument, the ICAP Technology Scale (ICAP-TS), was developed (Antonietti et al., 2023). The importance of ICAP in the context of this thesis helps to understand the student's perspective and complement the pedagogical design model to create cognitive and social engagement of the student through the mediation of TPRs.

Creating opportunities for social and physical presence in distance learning requires considering the prior experiences, beliefs, and readiness of both teachers and students, along with the organisation's technical, legal, and ethical preparedness. In addition, when used in the learning process, attention must be paid to the content and to the structure of the teaching process, that is, to instructional design, to ensure that technology supports the achievement of learning objectives. Furthermore, it is necessary to adapt the learning process so that, with the support of technology, opportunities arise for a constructive and interactive learning process. In the context of this thesis, particular attention is paid to develop a pedagogical design model with practical guidelines to support teachers, students, and technical support persons to implement TPRs in the learning and teaching process.

1.4 Challenges and Barriers in Telepresence Robots Adoption

For the effective implementation of TPRs in schools, it is crucial to address specific factors, such as ensuring robust internet infrastructure to support seamless connectivity and providing comprehensive teacher training to equip educators with the necessary skills to manage TPRs effectively. This applies to both the classroom and to the remote user, as well as to the technical readiness and stability of the TPR models. To ensure the meaningful participation of a remote student in the learning process, the audio-video signal must be intelligible and reach its destination with minimal delay (Capello et al., 2022; Powell et al., 2021; Weibel et al., 2024). Otherwise, the telepresence-mediated student is cut off from the teacher's cues, making it difficult to control the TPR from a distance (Okundaye et al., 2020). These technical factors affect the remote user's sense of social presence and increase their cognitive load. The introduction of TPRs enhances educational accessibility by allowing remote students to engage in real-time discussions, access diverse resources, and participate in interactive activities, as evidenced by studies showing increased participation rates and resource utilisation among remote students.

When implementing TPRs, it is essential to consider whether the learning environment allows the remote user to move autonomously or requires constant assistance from others (Capello et al., 2022; Weibel et al., 2024). Users with limited TPR experience may need an on-site support person to find an appropriate viewing angle and position in the room (Rode et al., 2024; Zand & Arif, 2025; Zhang et al., 2018).

Social aspects, such as how students interact with peers and the risk of social isolation, must be acknowledged, as they can significantly impact a student's engagement and sense of belonging in the educational environment. When participating via TPR, some students may feel excessive attention (Powell et al., 2021), which can be uncomfortable (Cha, et al., 2017). Although TPRs may reduce isolation, the effectiveness of interaction depends on the efforts of the teacher and classmates (Liao & Lu, 2018). Without the teacher's intentional process management, the teacher may inadvertently allow the remote students to take on a passive role during group work (Asadi & Fischer, 2025; Nordtug & Johannessen, 2023).

The pedagogical perspective must be considered, particularly in terms of adapting teaching methods to integrate TPRs and ensuring that remote students receive equitable educational experiences. Integrating TPRs into the classroom requires teachers to adapt by developing new instructional strategies, enhancing their technical skills, and fostering a more inclusive attitude towards remote students. They must adjust their teaching so that the remote participant can see, hear, and actively participate in lessons (Spoden & Ema, 2024). In addition, technical problems may arise, and resolving them is an extra burden that requires extra skills from teachers (Weibel et al., 2023). Implementing TPRs takes time and requires extra attention to ensure they are always ready for use (Jakonen & Jauni, 2021).

TPR-mediated participation in learning imposes a higher cognitive load than conventional face-to-face participation. Students must divide their attention between learning content, robot navigation, and technical issues. For students with health problems, dealing with multiple tasks at once may be exhausting (Johannessen et al., 2023). Moving through space via a robot may cause fatigue, as it differs from ordinary movement (Lu & Nishimura, 2024; Poyet, 2018).

Teachers and students are concerned about privacy and ethical factors, namely, what can be seen, heard, and recorded through the TPR. These questions form a distinct layer of obstacles (Huun & Slaven, 2024). Concerns about privacy and ethics influence the classroom climate, affecting both compliance with data protection requirements and the social atmosphere, as some students may feel limited in how openly they can behave (Adil et al., 2023).

At the organisational level, implementation is mainly influenced by two factor groups. The first includes determining factors such as the technical readiness of the infrastructure, including the internet quality and coverage, as well as the availability of support systems such as TPR management and help desk capacity (Spoden & Ema, 2024; Weibel et al., 2020). The second highlights how project-based and short-term implementation hinders systematic learning and the establishment of stable practices (Reyes-Cruz et al., 2024). Additionally, the high cost of TPRs affects implementation, preventing schools from acquiring them (Tota & Vaida, 2021). These challenges highlight the need for systematic guidelines, frameworks, or support materials that would help teachers, students, and organisations support or guide the implementation of TPR in education.

1.5 Pedagogical Design Models: Conceptual Foundations

Technology adoption frameworks, such as TAM, UTAUT, and TPACK, offer explanatory models for understanding how new technologies are accepted and implemented in educational contexts, including the readiness of teachers and students to use them (Davis, 1989; Mishra & Koehler, 2006). These frameworks operate primarily at the level of behavioural intention and perceived usefulness. However, they remain insufficient for structuring TPR-supported synchronous hybrid learning in ways that ensure inclusive participation and the social and embodied presence of remote participants.

A pedagogical model is a theoretical framework that guides learning practice (Chatez, 2025; Merrill, 2002) and draws on psychological, social, educational, and learning theories (Arufe-Giráldez et al., 2023; Behar, 2011). A pedagogical model provides the basis for planning teaching and learning processes (Arufe-Giráldez et al., 2023), making visible the relationships between teacher–student and environment (Zierer & Seel, 2012).

Pedagogical design can be understood as systematic choices based on procedures, methods, preconditions, and tools to ensure effective learning (Lowyck, 2002). Parallel concepts in the literature are instructional design and learning design. Traditions of instructional design have historically emphasised systematic procedures for analysing learning needs, defining objectives, developing learning materials, and evaluating learning outcomes (Branch, 2009). Learning design, in contrast, highlights the design of students' activities, interaction patterns, and contextualised tasks in specific environments (Goodyear & Retalis, 2010). Despite differences in emphasis, both traditions approach teaching as a purposeful and designable activity rather than an improvised practice (Laurillard, 2012).

A pedagogical design model is an applied framework that transforms theoretical principles into concrete and systematically organised learning architectures (Lowyck, 2002; Reigeluth et al., 2017). More broadly, a pedagogical design model creates a bridge between technology, theory, and real learning activity or provides clear guidelines or detailed procedures for solving problems or using technology in the learning process (Beisembayeva et al., 2023; Nonthamand, 2020). The term 'instructional design model' is more established and more widely institutionalised in international publications (Branch, 2009; Reiser, 2001). Often these are intended for developing systematic instructional planning, and the users are instructional designers (Khalil & Elkhider, 2016).

While instructional design models often emphasise structured phases of analysis, development, and evaluation (Branch, 2009; Reiser, 2001), a pedagogical design model highlights the configuration of roles, interaction patterns, participation structures, and learning activities within a specific environmental and organisational setting (Goodyear & Dimitriadis, 2013). This distinction is particularly relevant in TPR-supported hybrid learning, where effective implementation depends not only on systematic planning but also on the orchestration of presence, communication flows, and classroom ecology. Additionally, the pedagogical design model is used in contexts where technology integration is closely linked to the organisation of instruction, where technology integration is inseparable from the organisation of participation structures, spatial configurations, and communicative flows. The concept of a pedagogical design model therefore underscores the integration of theoretical assumptions, contextual constraints, and technological affordances into a coherent pedagogical architecture. It functions as a bridging construct between learning theory, instructional structuring, and technology-mediated classroom practice.

To clarify the conceptual distinctions discussed above, Figure 1 synthesises the relationship between pedagogical model, pedagogical design, and pedagogical design model within the broader dimension of technology integration. The figure illustrates that sustainable and pedagogically aligned technology integration constitutes a precondition for demonstrable students' competence and cognitive-social engagement. By separating technology integration outcomes from learning outcomes, the framework highlights that effective adoption and sustained integration are not equivalent to learning impact but rather serve as enabling conditions for it. This distinction provides a conceptual basis for analysing and developing structured pedagogical design approaches in technology-mediated learning environments.

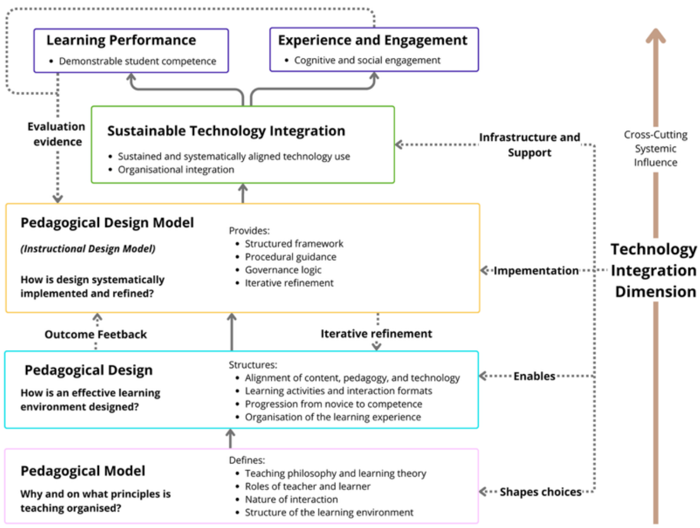

Figure 1. Conceptual relationship between pedagogical model, pedagogical design, and pedagogical design model within the technology integration dimension.

Several models have addressed aspects of TPR use in synchronous hybrid learning. The HANCON model (Han & Conti, 2020), which is based on UTAUT and post-acceptance theory (Bhattacherjee, 2001) proposes a technology adoption model adapted for TPRs. The focus of HANCON is on the factors that influence teachers' attitudes and behaviours in the effective TPRs use in the learning process. The model highlights important aspects such as social influence, expected performance, and effort, but it does not provide teachers with structured or step-by-step guidelines on how to use TPRs in the classroom.

The TRinE 4D pedagogical design model (Perifanou, 2023) supports the teacher in designing scenarios on how to use TPRs in the hybrid learning process. For the effective

TPR use in the learning process, the TRinE 4D model places the teacher's activities in defining the learning environment, planning the way TPRs will be used, and selecting teaching methods in an important position. Since the focus of the TRinE 4D model is on creating teaching scenarios, it does not offer support to students or for broader institutional adoption. In addition, it leaves aside the issues of the ethical TPR use and cognitive load and engagement.

4C model-based framework (Chan, 2024) proposes how to integrate TPRs into hybrid learning at the course level. The focus is on creating content, communication, collaboration, and coherence between in-class and remote students based on the specific nature of synchronous hybrid learning. The 4C model-based framework is not specifically designed for TPR integration but is intended more broadly to support the design of hybrid learning. Although valuable at the course-design level, the framework does not extend to embodiment-sensitive orchestration or system-level considerations required in robotic mediation. In addition, it does not address embodiment, cognitive load, or cybersecurity dimensions.

The focus of the existing models is either on technology adoption or on a scenario-based curriculum. None of them integrates environmental, ethical, pedagogical, cognitive, and inclusion-related dimensions into a unified architecture. This conceptual gap provides the rationale for the development of the PEPCII pedagogical design model introduced in this study.

Table 1 positions the result of this thesis in the pedagogical and adoption frameworks related to previous TPRs. The PEPCII pedagogical design model developed in this thesis is included for comparative purposes only, and its empirical development is described in subsequent chapters.

Table 1. Comparison of a telepresence robot adoption and pedagogical models.

Model	*Orientation*	*Level of analysis*	*Analytical contribution*	*Limitation for TPR use*
HANCON (Han & Conti, 2020)	*Technology acceptance*	*Individual (teacher)*	*Determinants of TPR adoption*	*No instructional design structure for organising learning activities*
TRinE 4D (Perifanou, 2023)	*Scenario-based hybrid pedagogy*	*Teaching scenario*	*Scenario-based hybrid lesson structure*	*Limited integration of ethical, environmental, and cognitive dimensions*
4C Model-based framework (Chan, 2024)	*Course-level Pedagogical design framework*	*Course level*	*Structured framework integrating content, collaboration, community, and communication within hybrid settings*	*Not specifically designed for TPR integration and does not address embodiment or cybersecurity aspects.*
Pedagogical design model developed in this study (PEPCII)	*Pedagogical design model*	*Multi-level*	*Integrative multi-dimensional pedagogical design framework*	*Detailed development and validation presented in Chapters 4–5*

The conceptual structure outlined in this chapter establishes the theoretical foundation for a systematic pedagogical integration of TPRs. It brings together the conditions for technology adoption, pedagogical design principles, and implementation processes within a coherent analytical framework. On this basis, the PEPCII pedagogical design model developed in this study is positioned as a structured, multi-level architecture for analysing and guiding the integration of TPRs in educational contexts. By distinguishing technology adoption outcomes from learning outcomes, the model avoids conflating implementation success with pedagogical impact. The following chapter presents the methodological approach used to develop and empirically investigate the model.

2 Methodological Framework

This chapter examines the philosophical underpinnings and frameworks of the pragmatic paradigm and Design-Based Research (DBR) methodology, which are central to studying TPRs in education.

The present work is grounded in the pragmatic paradigm (Morgan, 2007), which is particularly suited to research that aims to develop, test, and refine practical solutions to complex real-world problems. This paradigm values qualitative and quantitative research methods that help understand and evaluate educational innovations involving emerging technologies (Creswell & Clark, 2017). However, researchers must remain vigilant of their underlying assumptions to prevent the philosophical foundation of their work from becoming vague or contradictory (Morgan, 2007). Pragmatism's focus on practical utility and contextual applicability provides a strong foundation for integrating TPRs in education, as it allows for adaptable and effective solutions. A pragmatic stance enables the flexible use of both qualitative and quantitative methods to generate actionable and context-sensitive knowledge.

Accordingly, our study employed DBR as its overarching methodological framework. DBR provides a framework for systematically integrating TPRs into an educational environment that considers various social, pedagogical, and technological aspects. Given the iterative nature of DBR, the study progressed through successive phases of analysis, design, implementation, evaluation, and refinement, each informing the subsequent stage of development. This iterative process supported the gradual construction and validation of the PEPCII pedagogical design model. This methodological approach follows the principles established by the Design-Based Research Collective (2003) and elaborated by (Wang & Hannafin, 2005), emphasising the creation of sustainable, scalable educational innovations.

Design Thinking (DT) revolutionises problem-solving by focusing on user-centred solutions, which is crucial for effectively integrating TPRs in educational settings by addressing the specific needs of educators and students. It emphasises understanding and addressing the genuine needs of users rather than merely developing technical solutions (Brown, 2008). The DT approach is structured around five interrelated stages: empathise, which involves deeply understanding user needs; define, where the problem is articulated from a human-centred perspective; ideate, focusing on generating diverse ideas and potential solutions; prototype, involving the creation of preliminary models; and test, where these prototypes are evaluated with potential end users (Tham, 2022). In response to critiques that the five-step model has often failed to lead to practical implementation (Gekeler, 2019), a sixth stage, implement, was introduced to ensure that solutions are effectively applied in real-world contexts. This stage focuses on applying the developed solutions in real-life situations, thereby bridging the gap between conceptualisation and practical application.

The thesis combines several complementary frameworks that operate at different levels of the research process. Table 2 summarises their respective roles.

Table 2. Roles of the methodological components within the research framework.

Methodological element	*Function in the thesis*
Pragmatism	*Philosophical paradigm guiding the study*
Design-Based Research (DBR)	*Overall research methodology*
Design Thinking (DT)	*User-centred design process embedded within DBR cycles*
Technology Readiness Levels (TRL)	*Framework for describing model maturity and validation*

The use of TRL was particularly relevant because the PEPCII model extends beyond classroom pedagogy and addresses organisational and implementation conditions required for sustainable institutional adoption of TPR-supported hybrid learning.

Figure 2 illustrates how the pragmatic paradigm, DBR methodology, and DT process were operationalised throughout the three research phases of the study. The thesis follows DT logic and is organised into three DBR phases. The first phase, Exploration, incorporated the DT stages of Empathise and Define and focused on identifying pedagogical challenges related to TPRs, analysing the existing literature, and formulating design requirements for their educational implementation.

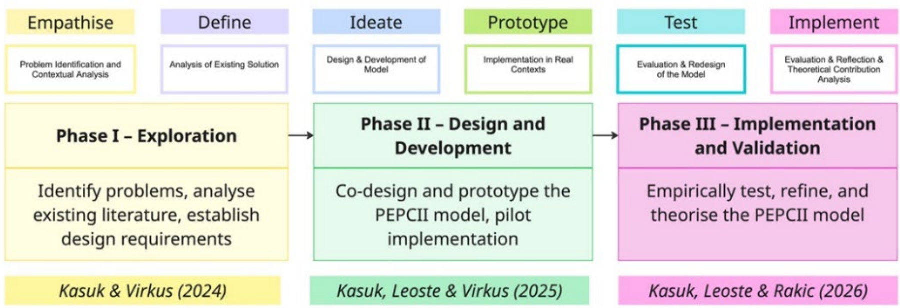

Figure 2. Study process in design-based research.

The second research phase, Design and Development, involved conducting DT stages Ideate and Prototype, where specific activities included brainstorming solutions and creating initial models. Through the empirical studies carried out in this phase, a prototype of the PEPCII pedagogical design model was developed and the created model was tested in both laboratory and real learning environments. The third phase, Implementation and Validation, included the DT stages Test and Implement, focusing on empirically validating and refining the model within a higher education setting.

Each phase informed the subsequent phase through iterative refinement. Findings from Phase I informed the initial design requirements of the PEPCII model. Insights obtained during Phase II resulted in revisions to the model prototype. Phase III provided empirical validation and further refinement of the model, thereby completing a DBR cycle of analysis, design, implementation, evaluation, and redesign.

The study integrates the TRL scale with DBR and DT approaches to provide a comprehensive assessment of the readiness of new technologies for market application, ensuring that the pedagogical design model is both innovative and practically applicable in educational settings (Mankins, 2009). The TRL scale is a nine-level scale that describes how ready technology is for the market (see Figure 3). This study relies on the TRL framework to evaluate the pedagogical-technological readiness of TPRs for large-scale implementation in school environments.

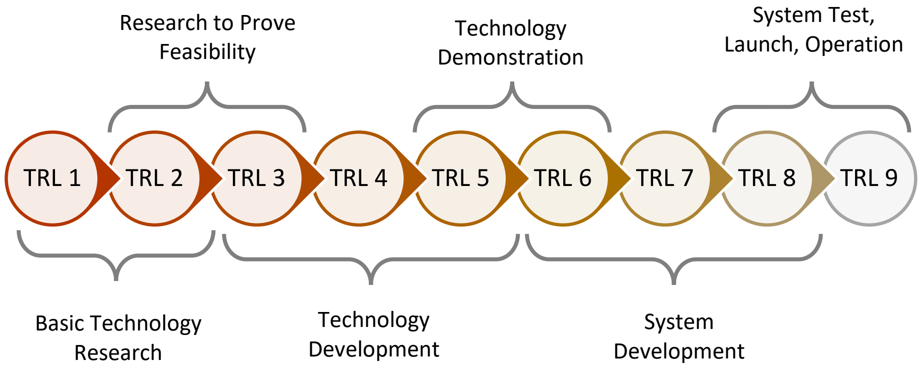

Figure 3. Overview of the Technology Readiness Level Scale by Mankin (2009).

The study's main outcome is a pedagogical design model that facilitates the adaptation of TPR to teaching and learning. The TRL scale remains relevant as it allows assessing the readiness of the model for practical application in educational settings. During the research, the developed pedagogical design model was prototyped, tested, and validated in a higher education context, confirming its applicability in real classroom settings.

The study was conducted in three iterative research phases, each yielding significant findings, such as the development of a validated pedagogical design model, which were published in peer-reviewed journals. Together, the three phases form a coherent DBR process that contributes to the advancement of educational technology integration. Table 3 provides an overview of the studies conducted in the three research phases, their objectives, the methods used, and the data collected and analysed.

Table 3. Overview of the three studies constituting the thesis, aligned with the Design-Based Research framework and illustrating the iterative process of exploration, design, and validation.

Phase	*Study*	*Aim*	*Core methodology*	*Key data sources*
Phase I – Exploration	*Exploring the Power of Telepresence (Kasuk & Virkus, 2024)*	*To analyse current research on TPRs and identify pedagogical gaps*	*Systematic literature review and bibliometric analysis*	*Scopus-indexed papers (n=53)*
Phase II – Design & Development	*Enhancing Synchronous Hybrid Learning with Telepresence Robots: The PEPCII Pedagogical Design Model (Kasuk et al., 2025)*	*To develop a pedagogical model addressing key barriers to TPR adoption*	*Design thinking-based co-creation*	*Needs analysis, student reflections, teacher workshop feedback*
Phase III – Implementation & Validation	*Validation of the PEPCII Pedagogical Design Model via Telepresence Robot Use in Higher Education (Kasuk et al., 2026)*	*To empirically test and refine the model in real classroom settings*	*Mixed-method evaluation*	*Surveys, focus groups, classroom observations, reflective feedback*

2.1 Phase I – Exploration

The first phase of the study combines the first two stages of design-based research, namely empathise and define, to identify problems, analyse existing literature, and establish design requirements. The aim of the initial phase of the study was to identify and analyse the current state of the art in the field of adapting TPRs into the educational setting. The results of this phase address the SRQ1: *What are the main pedagogical opportunities and challenges identified in existing research on integrating telepresence robots into educational settings?*

The systematic literature review was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009), which ensures a comprehensive and unbiased review process. The study was conducted using the SCOPUS database, where the search query (‘telepresence robot’ AND (‘learning’ OR ‘teaching’ OR ‘education’)) was applied to the fields’ titles, abstracts, OR keywords. The methodology is visually summarised in Figure 4. The time frame of the review covered the period up to 2 January 2023. Out of 127 scientific articles retrieved by the query, 53 were included in the systematic analysis because they were written in

English, had full texts available, and appropriately described the TPR use in the learning process, aligning with the research objectives.

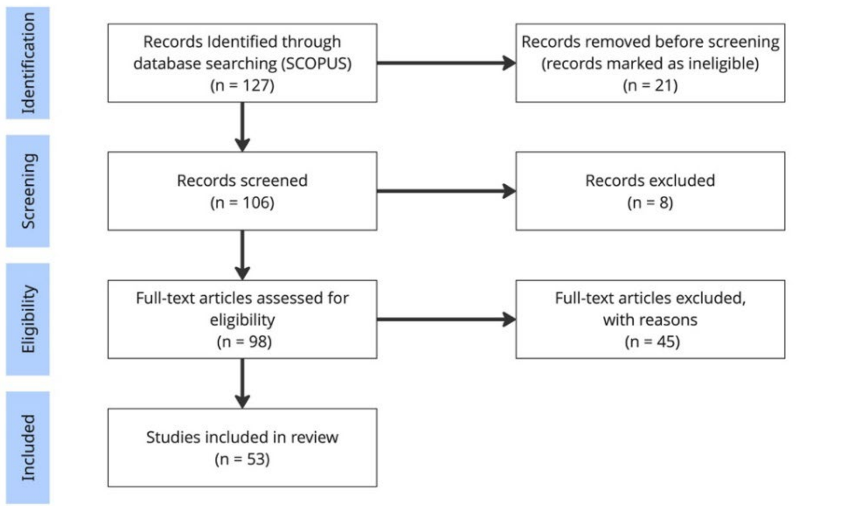

Figure 4. PRISMA flowchart of Publication I.

2.2 Phase II – Design and Development

The second phase of the study builds upon the findings of the first phase by transitioning from the initial research stages to the idea and prototype stages of design-based research. This phase focused on developing the pedagogical design model, which would guide teachers, students, and technical support in implementing TPRs in the educational environment. In addition, this phase piloted the developed pedagogical design model in the teaching and learning process. In this phase, three separate empirical studies were conducted, each informed by principles of the Design Thinking approach (Brown, 2008). Figure 5 visualises the activities and interconnections of the studies, illustrating the process flow and relationships within the research methodology. Total duration of the study was September 2023 to July 2024. The results of this phase address SRQ2: *How can a pedagogical design model be developed to support the effective and inclusive integration of telepresence robots in synchronous hybrid learning?*

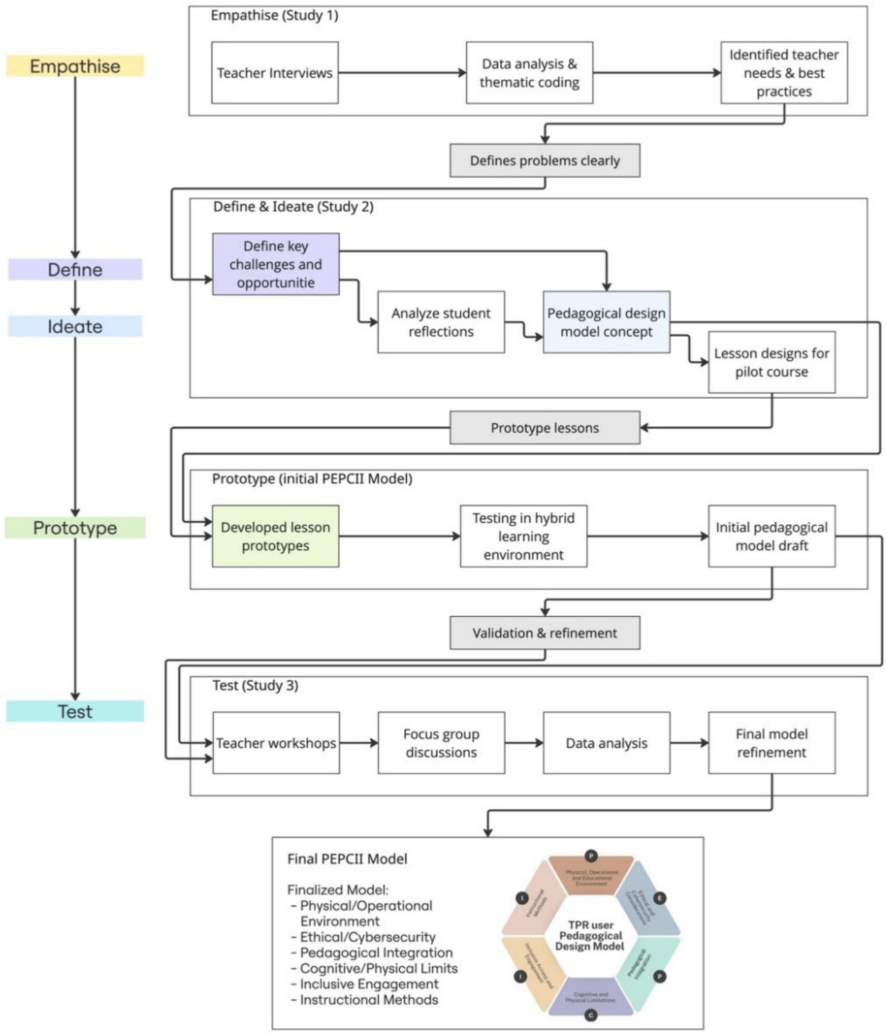

Figure 5. Flowchart of the PEPCII Pedagogical Design Model development.

In the first empirical study, conducted from September to November 2023, semi-structured interviews were held with Estonian higher education teachers. These teachers were experienced in using TPRs in teaching, and their insights were crucial for understanding practical applications. The study aimed to gather insights on the teachers' needs and best practices in using TPRs. Among the interviewed teachers, two were female and four male, with ages ranging from 30 to 67. As a result of the thematic analysis of the interview transcripts, the teachers' needs and best practices for using TPRs were identified.

The second empirical study built upon the findings of the first study, focusing on the identified needs and best practices for using TPRs. From February to May 2024, during a 13-week synchronous hybrid course, pilot lessons were implemented to explore how to effectively integrate TPRs into teaching practices. Six undergraduate students, aged below 30 years, participated in the course. The teaching took place in a real classroom, where teachers were present in person, while all students participated via TPRs. Throughout the course activities, six key aspects were explored that must be considered when applying TPRs in the learning process. The initial version of the PEPCII model was formulated based on a thematic analysis of student feedback, which included reflections from class and homework, alongside previous findings.

In the third empirical study, building on the outcome of the second study, the PEPCII model was validated. For validation, 13 workshops of 90 minutes' duration were conducted. Workshops were conducted from April to July 2024. In total, 56 teachers from Estonia and abroad participated. The participating teachers acquired baseline knowledge and skills for adopting TPRs in teaching. During the workshop, participants gained initial hands-on experience with TPR use and completed practical activities to understand the possibilities of TPR implementation. Following the workshop, focus group interviews were conducted with the 43 volunteer participants. All participants were asked for oral recommendations for analysing the transcripts of the focus group interviews. Based on the interview transcripts, a thematic content analysis (Smith, 1992) was conducted by one coder, which provided insights that were used to refine and improve the PEPCII model.

2.3 Phase III – Implementation and Validation

Building on the outcomes of the previous phases, the third phase focused on validating the PEPCII model in higher-education settings by testing it with real students and gathering data for improvements. This phase continued the design-based research process, moving from design and development towards practical validation in use. The activities were carried out in two Estonian universities over two academic semesters from October 2024 to May 2025. Telepresence participation was enabled through the TEMI robot, which played a crucial role in facilitating hybrid learning situations by allowing remote students to engage in real teaching contexts. The results of this phase address SRQ3: *How does the implementation of the PEPCII pedagogical design model demonstrate its practical applicability in supporting engagement, inclusion, and pedagogical alignment in higher education settings using telepresence robots?*

The study followed a convergent mixed-methods approach, collecting qualitative and quantitative data concurrently to enable triangulation of findings and to examine how the PEPCII model functioned in authentic instructional settings. This approach was aligned with a design-based research orientation, in which the model was not redesigned but applied as a design-informed framework to guide teaching and subsequently analysed through multi-stakeholder feedback. Figure 6 visualises the Phase III process in a flowchart, illustrating the sequence of design-informed preparation, classroom implementation, and reflexive analysis that underpin the validation of the PEPCII model.

Three participant groups were involved: teachers, TPR-mediated students, and in-class students. Sixteen teachers volunteered following an open invitation and an onboarding session introducing the PEPCII model and practical guidelines for TPR use. In total, 52 students participated remotely via TPRs, while 658 in-class students attended physically. These participants were engaged across multiple courses and disciplinary contexts, including computer science, social sciences, and engineering, enabling the examination of the model across diverse instructional settings. Data were collected through focus group interviews with teachers and TPR-mediated students, as well as written end-of-course feedback from in-class students, supporting a comprehensive, multi-perspective validation of the model in real-world higher education environments.

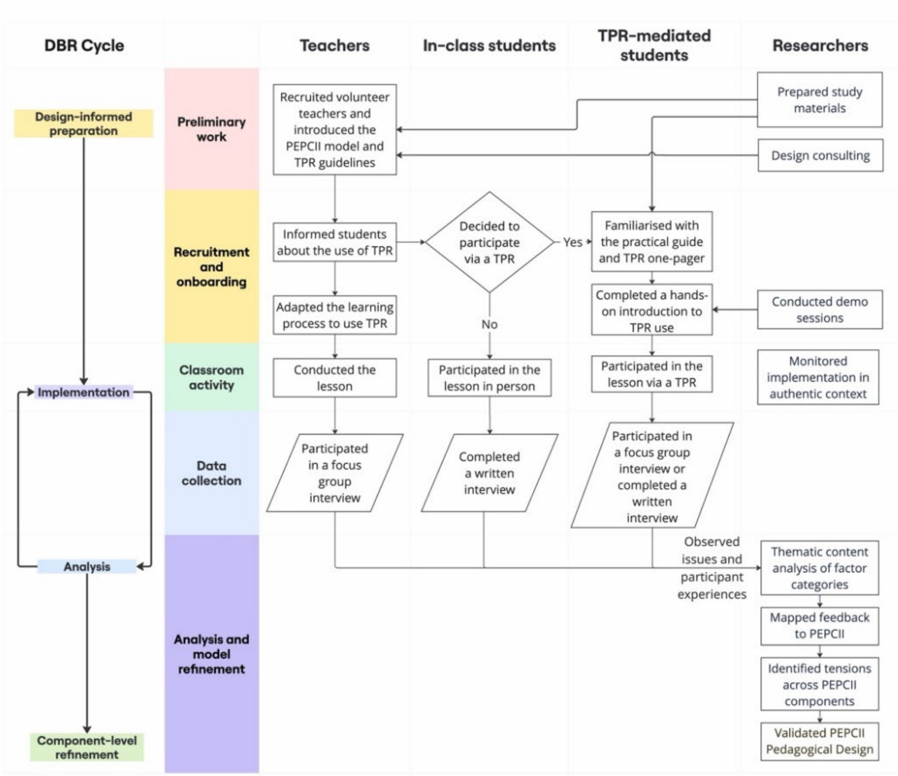

Figure 6. Flowchart of the PEPCII Pedagogical Design Model validation process.

Teachers (n = 10) participated in three focus groups. TPR-mediated students (n = 27) contributed either through eight focus group discussions (n = 17), conducted during the courses, or through written interviews (n = 10), completed via the MS Forms environment at the end of the courses. In-class students (n = 78) provided written responses following course completion. All focus group interviews were conducted via MS Teams, audio-recorded with participants' informed consent, and subsequently transcribed and manually verified for accuracy. Written data were collected using Microsoft Forms and integrated into the overall dataset to support triangulation across stakeholder groups.

The data were analysed using a reflexive thematic analysis approach, informed by the principles of thematic content analysis (Smith, 1992). The analysis proceeded inductively and iteratively through coding, constant comparison across data sources, and the development of higher-order themes related to engagement, inclusion, usability, and pedagogical alignment. The primary coding was conducted by one researcher, while a second researcher reviewed the evolving code structure and thematic interpretations; divergences were discussed until conceptual agreement was reached, thereby strengthening analytical rigour through reflexive dialogue. Following this first-stage inductive coding, refined abbreviations were introduced for the PEPCII components to support the subsequent analytical structuring of the data: Poe (Physical, Operational, and Educational Environment), E (Ethical and Cybersecurity Considerations), P (Pedagogical Integration), C (Cognitive and Physical Limitations), Ie (Inclusive Access and Engagement), and Im (Instructional Methods). These codes supported a more systematic organisation of the empirically generated themes and enabled clearer differentiation between closely related but analytically distinct PEPCII dimensions. Because they were introduced only after the initial inductive phase, the PEPCII model functioned primarily as an organising and validating analytical lens rather than as a strictly predefined coding scheme. The same abbreviations were then used consistently throughout the later analysis, including in Subsection 4.3.4.

The evaluation focused on four analytical dimensions: engagement, inclusion, usability, and pedagogical alignment. These dimensions were operationalised through qualitative indicators derived from participant experiences and perceptions, as well as through structured prompts in interviews and focus group discussions. Engagement and inclusion were examined in relation to participation, interaction, and sense of belonging; usability addressed the perceived ease of use and technical fluency of TPR-mediated learning; and pedagogical alignment focused on the coherence between teaching practices, learning objectives, and the PEPCII model.

The findings were further interpreted through the lens of Technology Readiness Levels (TRL) as an analytical framework for assessing the model's maturity and readiness for practical use in real-world educational contexts. Specifically, the evaluation was limited to TRL 7–9, corresponding to (1) demonstration of the model in authentic operational environments (TRL 7), (2) validation through multi-stakeholder use and feedback in real courses (TRL 8), and (3) confirmation of stable and sustained pedagogical functioning across courses and contexts (TRL 9). The empirical results, including course implementations, stakeholder feedback, and consistency of findings, were mapped against these TRL criteria to assess the level of operational readiness of the PEPCII model. The results were used both to refine the model at the component level and to confirm its pedagogical and technological readiness for sustained use within synchronous hybrid higher education settings, corresponding to TRL 9 in the investigated contexts.

Through this process, the PEPCII model was validated as a coherent and functional pedagogical framework for hybrid and inclusive learning environments. Validation was grounded in empirical evidence from authentic course implementations and multi-stakeholder feedback, demonstrating the model's practical usability, contextual relevance, and capacity to support teaching and learning. This marks a significant milestone in the design-based research cycle initiated in Phases I and II and confirms the model's readiness for practical application, corresponding to TRL 7–9, with evidence indicating stable and sustained use at TRL 9 within the studied contexts.

3 Empirical Foundations, Model Construction, and Validation

This chapter presents the empirical results of the study in relation to the research questions guiding the thesis. The results are reported based on three complementary empirical strands that together address the pedagogical use, development, and validation of the PEPCII pedagogical design model for TPR-mediated synchronous hybrid learning. In line with the purpose of the Results chapter, the findings are presented descriptively, without evaluative or theoretical interpretation. The implications of these results are examined in Chapter 5.

Section 4.1 reports the results of a systematic literature review addressing SRQ 1 and summarises existing research on the pedagogical opportunities and challenges associated with the TPR use in education. Section 4.2 presents the empirical findings informing the development of the PEPCII model based on three sequential empirical studies, addressing SRQ 2. Section 4.3 reports the empirical findings of the validation of the PEPCII model in authentic higher education teaching contexts, addressing SRQ 3 and focusing on the model's practical applicability and implementation conditions.

3.1 Evidence Base: Systematic Review of Telepresence Robot Pedagogy

This chapter is based on Publication **Error! Reference source not found.** and presents the results of the systematic literature review conducted to address SRQ 1: *What are the main pedagogical opportunities and challenges identified in existing research on integrating telepresence robots into educational settings?*

The review of the Scopus database was conducted using the PRISMA methodology. The final sample consisted of 53 peer-reviewed publications retrieved from the Scopus database. The results are divided into two complementary sections. First, a bibliometric analysis describes the main characteristics of the study, including publication types, temporal trends, and geographical distribution. Second, a thematic content analysis synthesises the main pedagogical themes emerging from the literature, focusing on the reported educational opportunities, uses, and challenges associated with TPRs.

The literature review was updated in early 2026 using the same search query and selection criteria, with the dataset extended to include studies published up to 2 February 2026. This update identified an additional 49 relevant publications, resulting in a total dataset of 102 studies. The expanded dataset was used to refine and extend the bibliometric analysis presented in Subsection 4.1.1, ensuring that the analysis reflects the most recent developments in the field. At the same time, the thematic analysis remains grounded in the originally and systematically analysed corpus to preserve methodological consistency and comparability across the phases of the study.

3.1.1 Bibliometric Structure of the Field

This subsection presents the results of a bibliometric analysis of the literature review. The initial analysis, based on 53 publications from 2011 to 2 January 2023, showed that more than half of the studies were conference papers (50.9%), followed by journal articles (45.3%), and a small proportion of book chapters (3.8%). After updating the literature search in early 2026, which included publications up to 2 February 2026, the dataset was expanded to 102 publications. The updated distribution of publication types shows that the ratio of conference and journal articles has become more balanced (see Table 4). Conference papers and journal articles both account for 48.0% of publications, while book chapters remain marginal (3.9%). Compared to the original dataset, where conference papers were more dominant, this shift reflects a stabilisation of publication patterns, where peer-reviewed journal articles are relatively more strongly represented alongside conference-based outputs.

Table 4. Distribution of papers by type (updated dataset, n = 102).

Type of the paper	*Count of papers*	*% of publications*
Book chapter	*4*	*3.9%*
Conference paper	*49*	*48.0%*
Journal article	*49*	*48.0%*
Grand total	*102*	*100.0%*

The temporal distribution of publications shows a continued and sustained growth in research activity. While the initial analysis identified 2020 as the most productive year (n = 13; 12.5%), the updated dataset indicates that publication output has not only remained high but has further increased in recent years. The year 2024 represents the peak of relevant research (n = 19; 18.3%), followed by consistently strong output in 2023 and 2025 (both n = 12; 11.5%). These findings suggest that interest in TPRs in education has not diminished after the COVID-19 period but has instead stabilised and expanded in the post-pandemic context. Figure 7 presents the updated distribution of publications by year.

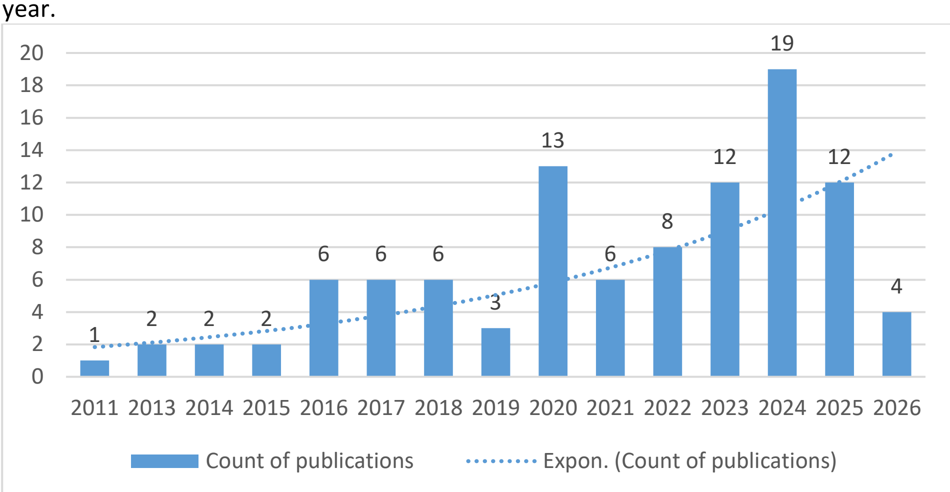

Figure 7. Distribution of publications on telepresence robots in education by year (2011–2026, updated dataset, n = 102).

The observed upward trend also reflects the increasing integration of telepresence technologies into mainstream educational research agendas, particularly in the context of hybrid and inclusive learning. Notably, the peak in 2024 surpasses the earlier pandemic-related peak observed in 2020, indicating that the field has transitioned from reactive adoption to sustained research and development.

Table 5 presents the geographical distribution of the reviewed publications by country. The geographical distribution of publications shows that the United States remains the leading contributor, accounting for 31 publications (30.4%). Estonia represents the second largest contribution with 8 publications (7.8%), followed by the United Kingdom with 5 publications (4.9%). Denmark and Finland each contributed 4 publications (3.9%), while Germany, France, Romania, and Japan each accounted for 3 publications (2.9%). Publications from smaller contributing countries (17.6%) and international collaborations (19.6%) account for over one-third of the dataset, highlighting the globally distributed nature of research on TPRs in education.

Table 5. Distribution of publications by country (updated dataset, n = 102).

Country	*Count of no*	*% of publications*
USA	*31*	*30.4%*
Estonia	*8*	*7.8%*
United Kingdom	*5*	*4.9%*
Denmark	*4*	*3.9%*
Finland	*4*	*3.9%*
Germany	*3*	*2.9%*
France	*3*	*2.9%*
Romania	*3*	*2.9%*
Japan	*3*	*2.9%*
Other	*18*	*17.6%*
International cooperation	*20*	*19.6%*
Grand total	*102*	*100%*

In addition, a notable proportion of the studies (n = 20; 19.6%) were conducted through international collaboration, highlighting the increasingly global nature of research in this field, compared to the initial dataset, where only 4 out of 53 publications (7.5%) involved multi-country collaboration and internationally connected research practices. This fivefold increase in international collaboration further reflects the growing complexity and interdisciplinarity of research on TPRs in education. The bibliometric analysis indicates that this research has evolved from an emerging field into a more established, internationally distributed, and collaborative area of study.

3.1.2 Thematic Conceptualisation

Following the bibliometric analysis, a thematic content analysis was conducted to systematically synthesise how TPRs are used as pedagogical tools across the reviewed studies. The analysis focused on reported didactic methods of using TPRs, TPRs for educational inclusivity, TPR robot as a teacher mediator and challenges related to the integration of TPRs in educational settings. Table 6 summarises the thematic categories and key pedagogical characteristics identified through the thematic content analysis of the reviewed studies.

Table 6. Thematic categories and key findings on the TPR use in education.

No.	*Thematic category*	*Key findings (brief description)*
1	*Didactic methods of using TPRs*	*TPRs are mainly used in situations where interaction and spatial presence are required. Common applications include participation by teachers, group work, discussions, and guest teaching. Use was often described in an activity-based manner, without systematic instructional design or a didactic framework.*
2	*TPRs for educational inclusivity*	*TPRs create opportunities for students to participate in education when physical presence is not possible (e.g. health-related constraints, geographical distance). Studies highlighted that the TPR use provides greater social presence, engagement, and a sense of belonging compared to conventional videoconference-based hybrid education.*
3	*TPR robot as a teacher mediator*	*TPRs create opportunities to involve a teacher or expert remotely to support interactive communication, guidance, and feedback. However, descriptions of the teacher's role and pedagogical responsibility were often limited in the studies.*
4	*Challenges in using TPRs*	*The main challenges are technical (connectivity, audio and video quality, narrow field of view, navigation and positioning) as well as organisational and social (technical support, user expectations, workload, acceptability). These limitations occur consistently across different educational levels and use cases.*

To further characterise the reported outcomes of a TPR use in education, the reviewed studies were examined for recurring pedagogical benefits and challenges. Table 7 summarises the reported pedagogical benefits and challenges associated with the TPR use in the reviewed studies.

Table 7. Benefits and challenges of using telepresence robots in education.

Reported benefits	*Reported challenges*
Social presence. TPRs increase students perceived presence and visibility in learning situations compared to conventional videoconferencing solutions.	*Network connectivity. Unstable internet connections affect the smoothness of communication and interrupt participation.*
Engagement and participation. Students can actively participate in discussions, group work, and classroom activities even from a distance.	*Audio and video quality. Audio delay, background noise, and visual disturbances limit the quality of interaction.*
Access and flexibility. TPRs enable participation in education when physical presence is hindered (e.g. health-related, geographical, or temporary constraints).	*Narrow field of view. Limited visual range makes it difficult to perceive the environment and non-verbal communication.*
Overcoming geographical barriers. Supports distance education, guest teaching, and international collaboration.	*Navigation and positioning. Moving within the space and finding an appropriate viewpoint require skills and environmental adaptation.*
Supporting interaction and collaboration. Enables more natural interaction between students and teachers.	*Technical and organisational support. The TPR use requires technical assistance, preparation, and time investment from both teachers and institutions.*

The results of the systematic literature review show that existing studies on the integration of TPRs in education mainly emphasise their use as tools to support interaction, social presence, and access to learning in situations where physical presence is limited. Several articles highlighted that the TPR use in synchronous hybrid learning creates the opportunity for active participation in text activities and ensures greater engagement in the learning process. At the same time, the results show that the TPR use in education is often described in an activity-based manner, neglecting a systematic approach to curriculum, didactic frameworks, or clearly defined pedagogical roles for teachers and students. Regardless of the educational context or level, the TPR use comes with technical, organisational, and social challenges, related to the need for connectivity, audiovisual quality, navigation, and institutional support. Overall, these results delineate the main pedagogical opportunities and challenges identified in existing research on the integration of TPRs into educational settings and provide an empirical foundation for the development of the PEPCII model presented in the following subsection.

3.1.3 Theoretical and Pedagogical Synthesis

The synthesis of the systematic literature review shows that existing research positions TPRs as tools that support and facilitate interaction, social presence, and access to learning in situations where physical presence is limited. In the analysed studies, TPRs are most frequently applied in activity-based learning situations, such as lectures, discussions, group work, and the inclusion of guests or experts in the classroom. This is particularly the case where spatial presence and interaction are pedagogically important.

At the same time, the literature shows that the pedagogical TPR use is rarely guided by systematic instructional design or explicit pedagogical frameworks. Although positive outcomes related to engagement, participation, and a sense of belonging are often reported, descriptions of pedagogical planning, role distribution, and didactic structuring remain limited. The teacher's role is often ambiguously defined, and pedagogical decisions are described primarily in terms of learning activities rather than as part of a coherent instructional planning process.

In addition, the reviewed sources highlight recurring technical, organisational, and social challenges associated with the TPR use, such as connectivity problems, audiovisual limitations, and navigation difficulties. These point to the need for sustained technical and institutional support. The same challenges appear consistently across different educational levels and contexts, indicating that they are not incidental but are closely linked to the implementation of TPR-mediated learning.

Overall, the literature points to a clear gap between the recognised pedagogical potential of TPRs and the lack of integrative pedagogical design approaches that would systematically address pedagogical, technical, and organisational considerations. This gap provides a strong rationale for the development of the PEPCII model, which aims to support the purposeful and sustainable integration of TPRs into synchronous hybrid learning.

3.2 Constructing the PEPCII Pedagogical Design Model

This chapter is based on Publication I and presents the empirical results informing the development of the PEPCII model for TPR users to address SRQ 2: *How can a pedagogical design model be developed to support the effective and inclusive integration of telepresence robots in synchronous hybrid learning?*

The development of the PEPCII model followed a sequential and iterative process based on three empirical studies, each contributing distinct yet interconnected design dimensions.

Figure 8 illustrates how three sequential empirical studies contributed complementary perspectives to the process of the model development. Each study built on the findings of the previous one, resulting in a progressive refinement of the PEPCII model from foundational implementation conditions to student-centred and institutional design dimensions.

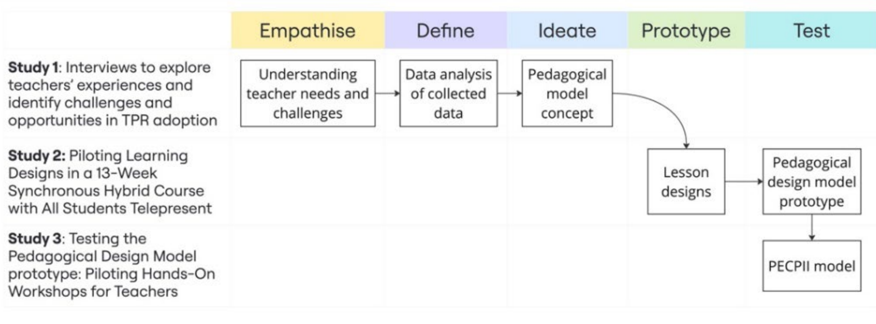

Figure 8. Iterative and cumulative empirical process informing the development of the PEPCII pedagogical design model.

The first study focused on teachers' practical experiences with TPR use, establishing the foundational pedagogical, technical, and organisational conditions necessary for implementation. The second study expanded the model by incorporating students' experiential perspectives, highlighting student-centred design considerations, cognitive load management, and ethical issues. The third study further refined and operationalised the model through teachers' professional development workshops, emphasising institutional readiness, training, and sustainable adoption practices.

3.2.1 Experiential Evidence from Teachers

The study focused on the technical and pedagogical experiences associated with the TPR use in the context of higher education, drawing on teachers' practical experience. Semi-structured interviews with six teachers who had used TPRs made it possible to identify the main factors influencing the quality of TPR implementation in synchronous hybrid learning. The results showed that TPRs are used primarily for three purposes: (1) enabling remote teachers to participate in teaching, (2) involving remote students in classroom activities, and (3) enabling the remote participation of teachers or experts in training sessions and academic events.

Teachers highlighted that, compared to conventional videoconferencing, TPRs offer higher social presence, allowing movement within the classroom, dynamic interaction, and more flexible participation in the learning process. However, teachers pointed out several technical limitations that directly affect the smoothness of teaching and student engagement. The most frequently mentioned problems were related to audio and video quality, including inadequate classroom acoustics, delays in audio transmission, and limited visibility in larger spaces. An unstable internet connection and the robot's slow movement speed caused interruptions and delays and hindered natural interaction.

From a pedagogical perspective, participants pointed out the limitations of non-verbal communication, which reduced the ability of TPR-mediated participants to use body language and eye contact. This, in turn, increased the need for conscious communication strategies and clear verbal instructions. In addition, teachers described increased cognitive load resulting from the need to teach, monitor technology, and solve problems simultaneously. Several participants emphasised that without additional technical support, the TPR use may lower teaching quality.

In addition, the study highlighted the importance of preparation and the central role of organisational support. According to teachers, successful TPR-based teaching requires thorough pre-testing, adaptation of the physical classroom environment, checking the reliability of equipment, and clear role allocation. The presence of a technical assistant was considered particularly important, as it allows the teacher to focus on conducting the lesson rather than resolving technical issues. The need for training and trial use was also emphasised, as these help teachers develop confidence and competence in using TPRs.

The key empirical findings related to teachers' experiences with TPRs are summarised in Table 8.

Table 8. Summary of the key empirical findings of teachers' experiences with telepresence robots.

Category of findings	*Description*	*Implications for teaching*
User experience	*Teachers' overall experience of using TPRs, including perceived opportunities and added value compared to videoconferencing*	*Shapes willingness to adopt TPRs*
Limitations	*Technical and pedagogical constraints, including audio and video quality, connectivity, infrastructure, cognitive load, and physical discomfort*	*May disrupt teaching and interaction*
Technical solutions	*Practical solutions for operating TPRs, including content sharing, robot positioning, and classroom setup*	*Supports smoother lesson delivery*
External help	*Need for assistants, technological aids, and support in situations where help is required*	*Enables teachers to focus on teaching*
Recommendations for beginners	*Advice on preparation, testing, and gradual familiarisation with TPRs*	*Reduces risks and increases confidence*

In summary, teachers' experiences demonstrated that while TPRs offer clear pedagogical added value in terms of social presence and interaction, their effective use is highly contingent on technical reliability, organisational support, and deliberate pedagogical planning. The findings revealed recurring challenges related to cognitive load, role distribution, and the integration of technological and instructional tasks. These results established the foundational structure of the PEPCII model by identifying core design conditions related to technical preparedness, support roles, and teacher readiness. As such, the first empirical study provided the initial framework upon which subsequent student-centred and institutional dimensions of the model were further developed.

3.2.2 Experiential Evidence from Students

This study focused on students' experiences of participating in synchronous hybrid learning through TPRs, with particular attention to social presence, engagement, cognitive load, and ethical considerations. The study was conducted during a 13-week undergraduate-level synchronous hybrid course in which all six participating students attended the course remotely via TPRs. Students' reflective assignments and written feedback provided insight into the factors shaping their learning experience and perceived effectiveness of TPR-mediated participation.

The findings indicated that students generally experienced a stronger sense of social presence and engagement when using TPRs compared to conventional videoconferencing tools. The ability to move independently within the classroom, choose interaction partners, and participate dynamically in discussions contributed to a heightened feeling of 'being present' in the physical learning environment. Students reported that TPR-mediated participation supported collaboration, particularly during group work, and facilitated more natural interaction with peers and teachers.

At the same time, the study revealed that a TPR use can impose a substantial cognitive load on students. Managing multiple interfaces simultaneously, such as the TPR control system, videoconferencing tools, and digital learning materials, required continuous attention and task-switching. This was particularly evident in situations where students were required to present content or actively navigate the classroom while engaging in learning activities. The findings showed that cognitive load could be reduced through practical measures such as the use of dual-screen setups, clearly structured digital materials, predefined classroom navigation paths, and explicit role distribution when multiple users interacted with the same TPR.

Ethical and cybersecurity considerations emerged as a further important theme. Students expressed concerns related to privacy, consent, and the potential for unintended access to sensitive information due to the mobility and camera capabilities of TPRs. Respectful interaction practices, clear rules for TPR use, and awareness of data security were identified as essential conditions for ensuring a safe and inclusive learning environment. These considerations influenced students' sense of comfort and willingness to engage actively in TPR-mediated learning activities.

In addition, the findings highlighted the importance of pedagogical design choices in supporting effective learning through TPRs. Students emphasised that the integration of digital collaboration tools, well-structured learning tasks, and clear instructions enhanced engagement and reduced frustration. When learning activities were explicitly designed to leverage the affordances of TPRs, students perceived the learning experience as more meaningful and less cognitively demanding.

The key empirical findings derived from students' lesson design reflections are summarised in Table 9.

Table 9. Summary of the key empirical findings of students' experiences with telepresence robots.

Category of findings	*Description*	*Implications for learning*
Environment and technical setup	*Physical learning environment, technical solutions, and infrastructure affecting visibility and usability*	*Influences accessibility and learning continuity*
Mobility and navigation	*Independent movement, spatial orientation, and navigation in the classroom*	*Supports situational awareness and presence*
Communication and interaction	*Audio and visual communication with teachers and peers*	*Shapes quality of interaction and participation*
Cognitive and physical limitations	*Cognitive load and physical constraints when using TPRs*	*May hinder sustained learning focus*
Social and ethical considerations	*Privacy, consent, and respectful interaction*	*Affects perceived safety and comfort*
Pedagogical integration and engagement	*Alignment of TPR use with learning activities and tasks*	*Enhances engagement and meaningful participation*
Recommendations for improved TPR experience	*Setup optimisation, pedagogical adjustments, and cognitive load management*	*Improves overall learning experience*
Potential applications and future directions	*Identification of promising use cases and development needs*	*Informs future pedagogical design*

Overall, the findings indicate that TPR-mediated participation can substantially enhance students' social presence and engagement in synchronous hybrid learning. At the same time, the study revealed that without explicit pedagogical and technical design measures, the cognitive demands associated with TPR use may hinder learning effectiveness. Ethical and cybersecurity concerns further emerged as integral conditions influencing students' sense of safety and willingness to participate. These informed the inclusion of the PEPCII model beyond teacher-centred implementation conditions by foregrounding student experience, cognitive load management, and ethical considerations as essential design dimensions. In this way, the second empirical study refined the emerging model by integrating student-centred and inclusive design principles.

3.2.3 Professional Knowledge Co-Construction

This empirical part focused on teachers' perspectives on the TPR use in education, drawing on feedback collected during a series of hands-on professional development workshops. A total of 56 teachers participated in synchronous hybrid workshops that combined remote participation via TPRs with in-person classroom activities. The workshops provided participants with practical experience in operating TPRs and enabled the collection of teachers' reflections on the applicability, benefits, and limitations of TPRs in real educational settings.

The findings indicated that teachers perceived TPRs as particularly valuable in educational scenarios where physical attendance is restricted but active participation is required. Such scenarios included situations involving illness, geographical distance, participation in training or professional development events, and access to specialised or restricted learning environments. Teachers emphasised that TPRs can support continuity of teaching and professional collaboration by enabling remote presence without fully replacing face-to-face interaction.

At the same time, participants identified several factors that influence the effectiveness of TPR use. A central theme was the need for technical and organisational support. Teachers repeatedly highlighted the importance of having a technical assistant or on-site support staff available during TPR-mediated sessions. The presence of such support was considered essential for addressing technical issues promptly and for allowing instructors to focus on pedagogical tasks rather than troubleshooting technology.

Preparation and training emerged as another critical factor. Teachers stressed that effective TPR use requires prior training, opportunities for hands-on practice, and gradual familiarisation with the technology. Professional development formats that combined theoretical explanations with practical experimentation were viewed as particularly beneficial for building confidence and competence. Participants also emphasised the value of pilot trials before implementing TPRs in regular teaching, as these help identify technical limitations and refine instructional strategies.

Ethical considerations were also discussed extensively during the workshops. Teachers raised concerns related to privacy, consent, and responsible TPR use in educational environments. The mobility and camera capabilities of TPRs were seen as creating potential risks if clear rules, and institutional guidelines are not in place. Participants emphasised the need for shared agreements on appropriate behaviour, transparent communication about data protection, and institutional policies to support ethical and secure TPR use.

In addition, the findings suggested that the number and quality of TPRs in use may influence the overall learning experience. Several teachers expressed the view that using a limited number of high-quality robots is preferable to deploying multiple devices simultaneously, as this reduces complexity and minimises disruptions. Participants also noted that classroom layout, infrastructure readiness, and stable internet connectivity play a significant role in determining whether TPR-mediated activities can be conducted smoothly.

The key empirical findings related to teachers' perspectives from the professional workshops are summarised in Table 10.

Table 10. Summary of the key empirical findings from teachers' professional development workshops.

Category of findings	*Description*	*Implications for teaching*
Training	*Need for structured training, supported practice, and opportunities to reduce fears and build confidence in using TPRs*	*Enables confident and effective TPR use*
Teacher preparation	*Importance of prior preparation, understanding limitations, and additional practice beyond workshops*	*Improves instructional readiness*
Student preparation	*Need to inform students about TPR use, clarify expectations, and adapt preparation to student needs*	*Supports smoother participation*
Assistant support	*Strong need for on-site technical assistance and support during TPR-mediated activities*	*Reduces disruptions during teaching*
Preparation before class	*Importance of environment design, material preparation, and pre-class testing*	*Avoids technical and pedagogical issues*
Usage experience	*Mixed experiences including benefits, challenges, best practices, and technical issues*	*Informs realistic adoption strategies*
Use cases	*Identification of suitable and unsuitable scenarios for TPR use in education*	*Supports informed pedagogical decisions*
Other considerations	*Ethical aspects, teacher readiness, number of robots, and future development needs*	*Ensures responsible and sustainable implementation*

In conclusion, the workshop-based findings indicated that teachers perceive TPRs as a viable and promising educational tool when their use is supported by structured training, technical assistance, and clear ethical guidelines. The study highlighted the importance of institutional readiness, realistic use-case selection, and sustainable implementation strategies grounded in everyday teaching practice.

These findings contributed to the further refinement and validation of the PEPCII model by translating previously identified pedagogical and student-centred design conditions into professional practice and organisational contexts. As such, the third empirical study operationalised the model, strengthening its applicability for real-world educational settings.

3.2.4 Derivation of Core Design Dimensions

This subsection synthesises the findings of the three empirical studies by relating them explicitly to the design dimensions of the PEPCII model. The empirical findings are then mapped to the model dimensions without theoretical interpretation. Each subsection corresponds directly to one visual dimension of the model, describing how empirical observations across studies relate to each dimension.

Physical, Operational, and Educational Environment (P). Across all three studies, participation in a lesson mediated by a TPR was associated with the physical environment and its configuration. From the teachers' interviews, it was reported that the experience and the course of the learning process were most strongly influenced by the classroom layout, acoustics, the positioning of the TPR, and the readiness of the infrastructure. Students' feedback likewise referred to issues related to the environment and technical setup that affected accessibility and situational awareness. Participants in the workshops referred to the need for prior practice, adaptation of the space to the needs of the TPR, stable internet, and the availability of technical support. These observations indicate that aspects of the physical, operational, and educational environment were present across all three studies.

Ethical and Cybersecurity Considerations (E). Ethical and cybersecurity issues affecting the sense of safety, comfort, and readiness of both TPR-mediated and other participants were identified in all three empirical studies. Students and teachers referred to concerns related to privacy, consent, and responsible use. Workshop participants pointed out the need for institutional guidelines and transparent communication. These findings show that ethical and cybersecurity aspects were consistently associated with participants' sense of safety and readiness.

Pedagogical Integration (P). Across the studies, pedagogical integration was emphasised as the alignment of TPR use with learning objectives, participation, assessment, and learning activities. Participants referred to situations in which the adoption of TPRs was considered in relation to intended learning outcomes, the design of learning activities, and assessment requirements. Participants highlighted the importance of integrating TPRs into the learning process rather than treating them as additional tools. Students reported higher engagement when learning activities supported interaction and participation through TPRs. Teachers stressed the need to align participation structures, learning activities, and assessment practices with TPR affordances and limitations at both course and lesson levels. Workshop participants discussed learning scenarios where TPR use was pedagogically appropriate or inappropriate. These observations relate to the Pedagogical Integration component of the PEPCII model, which focuses on aligning TPR use with overall learning design.

Cognitive and Physical Limitations (C). The results of all studies contained references indicating that participation mediated by TPRs involves both cognitive and physical constraints. Teachers reported that their cognitive load increased during the teaching process when they had to simultaneously teach TPR-mediated students, support the use of technology, or deal with technical problems. Students reflected that their cognitive load increased when they had to use multiple software tools or understand spatial arrangements. In addition, they referred to physical fatigue during longer periods of participation in TPR-mediated learning. Workshop participants referred to the importance of work processes being simple, roles clearly defined, and the availability of technical support as factors related to managing these constraints. These observations indicate that cognitive and physical constraints were present across studies at both the organisational and user levels, from both teachers and students.

Inclusive Access and Engagement (I). This was identified as the cross-cutting theme of the three empirical studies. Teachers and students observed that TPRs are suitable for use in situations where physical presence is not possible, such as illness, geographical distance, or other factors. For students, the TPR use was associated with increased inclusion through the autonomy provided, opportunities for movement, and the facilitation of social interaction in classroom activities. Teachers referred to TPRs as enabling opportunities to maintain continuity and equity in learning. Workshop participants noted that, to create effective communication between in-class and remote students, preparation of both parties is required. These findings relate to the inclusive access and engagement component in the pedagogical model.

Instructional Methods (I). The effectiveness of TPR-mediated participation depended on pedagogical decisions and structured preparation and implementation support. Teachers emphasised practical guidance, TPR examples, and opportunities to familiarise themselves with TPR functionalities before use. Students highlighted clear participation instructions, onboarding activities, and technical support when difficulties arose. Successful TPR use was associated with rehearsal opportunities, operational guidance, and clear expectations. Workshop participants noted that both teachers and students require adequate preparation and support to use TPRs effectively. These observations relate to the Instructional Methods component of the PEPCII model, which focuses on implementation-oriented practices that facilitate successful TPR-mediated participation.

Taken together, the three empirical studies provide a cumulative description of how technical, pedagogical, student-centred, ethical, and environmental considerations were observed across multiple empirical contexts involving the effective and inclusive integration of TPRs in synchronous hybrid learning.

The derivation of the PEPCII dimensions was also informed by the pedagogical synthesis reported in Publication I. The literature review identified eight educational scenarios and eight didactical methods through which TPRs were applied in educational contexts. While these scenarios and methods were not incorporated into the model as separate components, they provided important pedagogical evidence for the development of the higher-level PEPCII dimensions. Table 11 illustrates how the didactical methods identified in Publication I align with the dimensions of the PEPCII pedagogical design model.

Table 11. Alignment of the didactical methods identified in literature with the dimensions of the PEPCII pedagogical design model.

Didactical method identified in Publication I	*PEPCII dimensions primarily informed*
Practical skills and teamwork	*Pedagogical Integration (P); Instructional Methods (I)*
Remote laboratory work	*Physical, Operational, and Educational Environment (Poe); Pedagogical Integration (P); Instructional Methods (I)*
Workshops and hands-on learning	*Pedagogical Integration (P); Instructional Methods (I)*
Foreign language teaching	*Pedagogical Integration (P); Instructional Methods (I)*
Virtual field trips	*Physical, Operational, and Educational Environment (P); Pedagogical Integration (P); Instructional Methods (I)*
Integrating segregated educational environments	*Inclusive Access and Engagement (I); Pedagogical Integration (P)*
Storytelling and vocabulary learning	*Pedagogical Integration (P); Instructional Methods (I)*
Synchronous hybrid learning	*All PEPCII dimensions*

The literature review identified eight educational scenarios and eight didactical methods through which TPRs were applied to educational contexts. While these scenarios and methods were not incorporated into the model as separate components, they informed the development of the higher-level PEPCII dimensions. Table 11 illustrates this relationship.

3.2.5 Model Specification

The PEPCII conceptualises the identified design dimensions into a structured framework for adapting TPRs in the synchronous hybrid learning. As illustrated in Figure 9, the model is organised around six pedagogical design dimensions and places the TPR user at the centre of the pedagogical design, emphasising a user-centred rather than a technology-driven perspective.

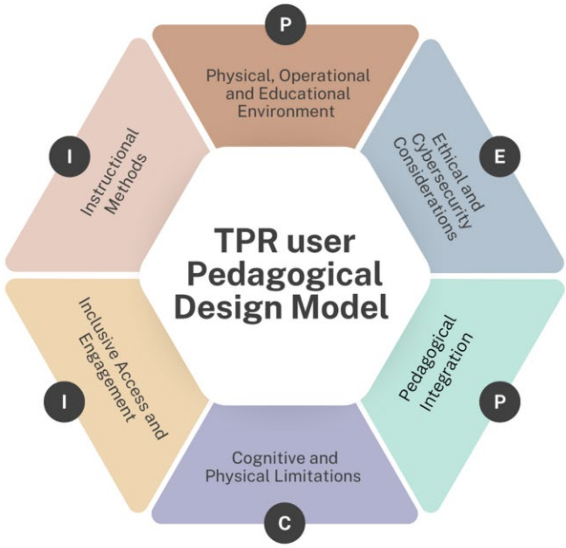

Figure 9. The PEPCII pedagogical design model illustrating the interrelated pedagogical design dimensions relevant to telepresence robot-mediated synchronous hybrid learning.

The PEPCII model consists of six interrelated pedagogical design dimensions: Physical, operational, and educational environment (P); Ethical and Cybersecurity Considerations (E); Pedagogical Integration (P); Cognitive and Physical limitations (C); Inclusive Access and Engagement (I); and Instructional Methods (I). While instructional methods are traditionally considered a component of pedagogical design, the distinction between Pedagogical Integration and Instructional Methods in the PEPCII model emerged from empirical findings obtained during the model development and validation studies. Within the model, Pedagogical Integration focuses on aligning TPR use with learning objectives, participation, assessment, and learning activities, whereas Instructional Methods refers to implementation-oriented practices that support the effective TPR use in educational settings. These include onboarding, training, technical support, rehearsal opportunities, operational guidance, and other forms of practical support required for successful TPR-mediated participation. Table 12 summarises the components of the PEPCII model, outlining their analytical focus and the key empirical findings and pedagogical implications derived from the analysed studies.

Table 12. Empirically grounded components of the PEPCII pedagogical design model.

Component	*Focus*	*Empirical findings and pedagogical implications*
Physical, Operational, and Educational Environment (P)	*Classroom layout, robot placement, visibility, and technical infrastructure*	*Environmental factors directly influence the quality of interaction and the perceived legitimacy of TPR-mediated presence. A well-considered spatial and technical setup is a prerequisite for meaningful participation.*
Ethical and Cybersecurity Considerations (E)	*Privacy, data protection, and social norms*	*Teachers and students emphasised the need for clear guidelines and shared agreements to support trust and the responsible TPR use, especially about visibility and recording capabilities.*
Pedagogical Integration (P)	*Alignment of TPR use with learning objectives, participation, assessment, and learning activities*	*Effective TPR implementation requires deliberate alignment between learning outcomes, participation structures, assessment approaches, and the affordances and limitations of TPR-mediated participation.*
Cognitive and Physical Limitations (C)	*Cognitive load and physical fatigue*	*Prolonged TPR-mediated participation may cause fatigue and limited situational awareness; instructional design must balance movement, interaction, and cognitive load.*
Inclusive Access and Engagement (I)	*Access, social presence, and sense of belonging*	*Although TPRs enable participation in the absence of physical presence, engagement depends on intentional design. Technological access only does not ensure engagement without practices that support social presence.*
Instructional Methods (I)	*Preparation and support for effective TPR-mediated participation*	*Effective TPR use depends on practical implementation measures such as onboarding, demonstrations, technical support, rehearsal opportunities, FAQs, and clear participation guidelines that help teachers and students use TPRs confidently and effectively.*

While the preceding sections have outlined the empirically grounded components of the PEPCII model and their analytical focus, the integration of these components into a coherent pedagogical framework requires explicit consideration of the model's pedagogical orientation. The following section therefore describes how the PEPCII model is pedagogically positioned, clarifying the underlying instructional assumptions and the way in which its components collectively guide teaching and learning practices in TPR-mediated synchronous hybrid environments.

3.3 Validation Across Stakeholder Groups

This chapter builds on Publication II and presents empirical findings that inform the validation of the PEPCII model in synchronous hybrid learning contexts in higher education. The purpose of this chapter is to address SRQ 3: *How does the implementation of the PEPCII pedagogical design model demonstrate its practical applicability in supporting engagement, inclusion, and pedagogical alignment in higher education settings using telepresence robots?*

The validation of the PEPCII model was conducted through a design-based study, implemented in authentic higher education courses and involving three stakeholder groups, including teachers, TPR-mediated students, and in-class students attending in person. The validation of the PEPCII model focused on examining its practical applicability, usability, and stability in authentic educational settings, rather than aiming to measure learning effectiveness or to compare learning outcomes.

The validation process was based on sustained use of the PEPCII model across multiple courses, during and after which empirical data were collected from multiple stakeholders. Data analysis examined how pedagogical, technical, cognitive, ethical, and engagement-related considerations manifested in TPR-mediated synchronous hybrid learning. This allowed for the identification of recurring patterns, constraints, and enabling conditions that supported or limited the use of the model in practice in operational educational settings.

3.3.1 Teacher-Level Validation

This subsection presents the teachers' perspective on the implementation of the PEPCII model in synchronous hybrid learning. The analysis is based on focus group data from participating teachers (n = 10) and is structured according to four analytical dimensions: engagement, inclusion, usability, and pedagogical alignment. To enhance transparency, coded segments derived from thematic analysis were grouped into these dimensions and quantified.

The distribution of coded segments across the four dimensions is presented in Table 13.

Table 13. Teacher-level validation of the PEPCII model based on coded focus group data.

Dimension	*Number of coded segments (n)*	*Dominant pattern*	*Empirical interpretation*
Engagement	*18*	*Mixed (active + constrained)*	*Engagement depends strongly on teacher orchestration and visibility of remote students.*
Inclusion	*4*	*Conditional*	*Inclusion is possible but requires active facilitation and social integration.*
Usability	*14*	*Predominantly constrained*	*Technical limitations (audio, video, control) significantly affect teaching.*
Pedagogical alignment	*20*	*Strongly supportive*	*The model supports structured teaching but requires adaptation of activities.*

As shown in Table 13, pedagogical alignment emerged as the most prominent dimension in teachers' accounts, followed by engagement. Usability-related issues were also frequently reported, while inclusion-related references were comparatively limited. This pattern is further illustrated in Figure 10.

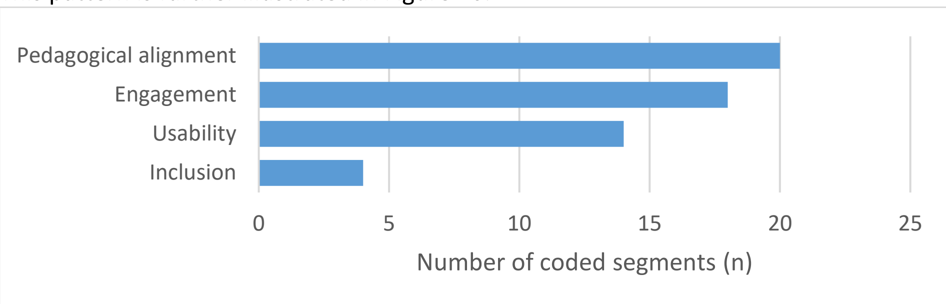

Figure 10. Distribution of coded teacher responses across PEPCII analytical dimensions based on focus group data (n = 10).

The findings indicate that the PEPCII model provides a strong framework for structuring teaching activities and supporting pedagogical planning. Teachers consistently emphasised that successful implementation depends not on the technology itself but on deliberate pedagogical preparation. This included planning interaction structures, defining participation roles, and adapting lesson design to accommodate TPR-mediated participation. As one teacher noted, *I planned in advance how those in the robot would participate*.

At the same time, the data reveal that engagement in TPR-mediated learning is not automatically achieved. Teachers reported that maintaining engagement required continuous monitoring and active orchestration, particularly in ensuring that remote students remained visible and included in classroom interaction. Several participants described the need to repeatedly check whether remote students could see, hear, and follow the lesson, highlighting the importance of teacher-led facilitation.

Usability emerged as a significant constraint in the implementation process. Teachers frequently reported technical challenges related to audio quality, visual access, and system coordination. These issues increased cognitive load, as teachers were required to simultaneously manage teaching, technology, and classroom dynamics. Situations where real-time technical support was unavailable were described as particularly demanding, reinforcing the importance of support structures within the PEPCII model.

In contrast, inclusion was less frequently addressed in explicit terms, suggesting that it does not emerge as an automatic outcome of TPR use. Instead, inclusion depended on deliberate pedagogical and social practices, such as acknowledging remote students, positioning the robots effectively, and integrating them into group activities. Without such practices, remote participants risked remaining peripheral to the learning process.

Finally, the findings highlight the importance of pedagogical fit. Teachers reported that TPRs were most effective in structured, lecture-based or low-mobility learning environments, whereas spontaneous group work and practical activities were more difficult to manage. This confirms the importance of aligning activity design with the affordances and limitations of TPR-mediated participation. The results demonstrate that while the PEPCII model provides strong support for pedagogical alignment and structured teaching design, its effectiveness depends on the interplay between pedagogical planning, technical conditions, and active facilitation of participation.

3.3.2 Validation by TPR-Mediated Students

This subsection presents the perspectives of TPR-mediated students on participation in synchronous hybrid learning. The analysis is based on coded qualitative data from student participants and is structured according to the four analytical dimensions of the PEPCII model: engagement, inclusion, usability, and pedagogical alignment. To improve analytical clarity, coded segments were grouped into these dimensions and quantified.

The distribution of coded segments is presented in Table 14.

Table 14. Validation of the PEPCII model from the perspective of TPR-mediated students based on coded qualitative data.

Dimension	*Number of coded segments (n)*	*Dominant pattern*	*Empirical interpretation*
Engagement	*30*	*Predominantly constrained*	*Students frequently experienced passivity, exclusion, and limited participation.*
Inclusion	*8*	*Weak / inconsistent*	*Inclusion was situational and often incomplete.*
Usability	*74*	*Strongly constrained*	*Technical issues dominated the student experience.*
Pedagogical alignment	*25*	*Conditional*	*Effectiveness depends on task type (lecture vs group work).*

As shown in Table 14, usability emerged as the dominant dimension in students' accounts, clearly outweighing all other dimensions. This pattern is further illustrated in Figure 11.

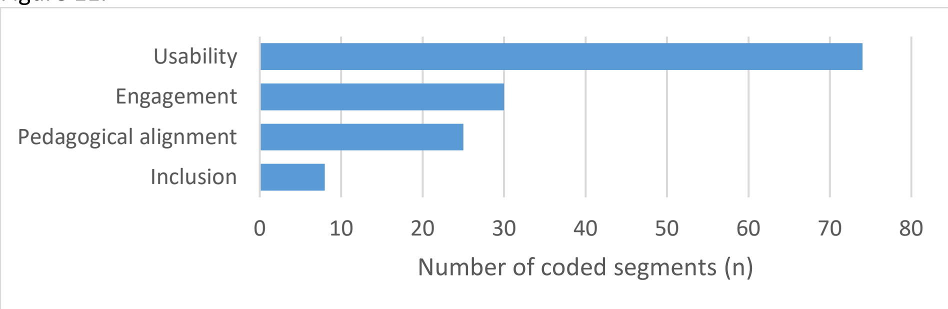

Figure 11. Distribution of coded segments across PEPCII dimensions based on TPR-mediated student data.

The findings indicate that, from the students' perspective, the effectiveness of TPR-mediated participation is strongly constrained by technical and operational factors. Students frequently reported issues related to audio quality, video clarity, navigation control, and system stability. These issues significantly affected their ability to follow the lesson and participate actively. As one participant noted, *I could barely understand the lecture*, while another described how *there was more effort spent on managing the robot than on listening*.

In addition to usability challenges, engagement was often limited. Many students described experiences of passivity, reduced interaction, and peripheral participation. In several cases, students reported feeling excluded from classroom activities, particularly during group work or practical tasks. One participant stated, *I felt like an observer rather than a participant*, while another noted that *we still felt like outsiders*. These findings suggest that engagement in TPR-mediated environments does not occur automatically and requires structured pedagogical support.

Inclusion was addressed less frequently and appeared as a conditional outcome rather than a consistent experience. While some students reported feeling socially included and able to interact with peers, others highlighted a lack of social presence and difficulties in communication. Inclusion was therefore dependent on contextual factors such as classroom organisation, teacher facilitation, and technical functionality.

From a pedagogical perspective, students consistently emphasised that the suitability of TPR-mediated participation depends on the type of learning activity. Lecture-based formats were generally perceived as appropriate, whereas group work, discussions, and practical activities were often described as problematic. As one participant explained, *If there is a lot of group work, I would rather go on site*. This confirms the importance of aligning pedagogical design with the affordances and limitations of telepresence technologies.

At the same time, students acknowledged the flexibility and accessibility benefits of TPR use. Several participants highlighted its value in situations where physical attendance was not possible, such as illness or geographical constraints. However, these benefits were often framed as compensatory rather than equivalent to in-person participation.

Overall, the results demonstrate that while the PEPCII model provides a relevant framework for understanding TPR-mediated participation, its successful implementation from the student perspective depends heavily on resolving usability challenges and ensuring pedagogically structured interaction. The findings highlight a clear discrepancy between pedagogical potential and lived user experience, emphasising the need for integrated design that addresses both dimensions simultaneously.

3.3.3 Validation by In-Class Students

This subsection presents the perspectives of students physically present in the classroom during TPR-mediated hybrid learning sessions. Unlike teachers and TPR-mediated students, in-class participants did not directly experience remote participation but instead reflected on the presence and impact of TPRs from an observer perspective. The analysis is structured according to the four analytical dimensions of the PEPCII model.

The distribution of coded segments is presented in Table 15.

Table 15. Validation of the PEPCII model from the perspective of in-class students based on coded qualitative data.

Dimension	*Number of coded segments (n)*	*Dominant pattern*	*Empirical interpretation*
Usability	*32*	*Concern-driven*	*In-class students questioning technical reliability and performance*
Inclusion	*28*	*Uncertainty-focused*	*Strong concern about remote students' visibility, participation, and inclusion*
Pedagogical alignment	*12*	*Critical*	*Doubts about suitability, especially for group work*
Engagement	*6*	*Indirect*	*Engagement considered mainly from comparison perspective*
Preparation / awareness	*10*	*Information-seeking*	*Need for understanding how the system works and how it is used*

As shown in Table 15, usability and inclusion emerged as the most prominent dimensions in in-class students' accounts. This pattern differs significantly from both teachers and TPR-mediated students, reflecting the observational and interpretive nature of their perspective.

In-class students frequently raised concerns about whether remote participants were able to see, hear, and follow the lesson effectively. Questions such as *Can they hear us well enough?* and *What do the students on the other side of the screen see?* illustrate a strong awareness of potential asymmetries in participation. These concerns indicate that inclusion is not only a pedagogical issue but also a perceived social responsibility among co-present students.

Usability-related concerns were also prominent, particularly regarding audio quality, video clarity, and control of the robot. In-class students observed technical limitations both directly and indirectly, often questioning whether the system functioned reliably and whether it might disrupt the classroom environment. For example, participants noted issues such as unclear audio, excessive noise, and limited mobility of the robot.

From a pedagogical perspective, students expressed doubts about the suitability of TPR-mediated participation for interactive learning activities. Group work emerged as a particularly problematic area, with several participants questioning whether remote students could meaningfully contribute. One participant described the situation as *chaotic, especially during group work*, highlighting the challenges of integrating remote participants into collaborative learning processes.

Engagement was addressed less frequently and primarily through comparison with physical participation. In-class students questioned whether remote participation could provide an equivalent learning experience, often expressing scepticism about its effectiveness. This perspective was reflected in statements such as *Is it equivalent to being physically present*? and *How involved can they be compared to in-class participants*?

In addition to these dimensions, a notable proportion of responses focused on preparation and awareness. In-class students expressed a clear need for information about how the system works, how it is used, and what its purpose is within the learning process. This suggests that transparency and shared understanding are important factors in supporting the acceptance and effective integration of telepresence technologies.

The findings indicate that in-class students play a critical role in the success of TPR-mediated learning environments. Their perceptions highlight the importance of visibility, communication clarity, and pedagogical integration, as well as the need to address ethical and social considerations. Unlike remote participants, whose experiences are shaped by direct interaction with the system, in-class students assess its effectiveness through observation, comparison, and reflection.

3.3.4 Consolidated Validation Findings

To further validate the PEPCII pedagogical design model, a cross-stakeholder analysis was conducted based on the coded empirical data derived from Publication III. The distribution of coded segments across teachers, in-class students, and TPR-mediated students is presented in Table 16. The table provides a comparative overview of the relative prominence of each PEPCII dimension across stakeholder groups, revealing systematic differences in how TPR-mediated learning is experienced and interpreted.

Table 16. Cross-stakeholder distribution of coded segments across PEPCII model components.

PEPCII component	*Code*	*Teachers (n)*	*In-class students (n)*	*TPR-mediated students (n)*	*Relative prominence*
Physical, Operational, and Educational Environment	*Poe*	*29*	*32*	*85*	*Dominant (all groups)*
Ethical and Cybersecurity Considerations	*E*	*1*	*18*	*2*	*Dominant (in-class only)*
Pedagogical Integration	*P*	*27*	*8*	*26*	*Dominant (teachers & TPR)*
Cognitive and Physical Limitations	*C*	*6*	*8*	*35*	*Dominant (TPR)*
Inclusive Access and Engagement	*Ie*	*17*	*24*	*52*	*Dominant (students)*
Instructional Methods	*Im*	*8*	*13*	*61*	*Dominant (TPR)*

The results demonstrate that the Physical, Operational, and Educational Environment (Poe) constitutes the most dominant component across all stakeholder groups (teachers n = 29; in-class students n = 32; TPR-mediated students n = 85). This consistent prominence indicates that environmental and technological conditions form the foundational layer of TPR-mediated participation. The substantially higher frequency among TPR-mediated students further suggests that remote participants are particularly sensitive to constraints related to audio quality, visibility, mobility, and system reliability.

This is also reflected in teacher accounts emphasising the need for deliberate spatial organisation:

> *… we had to arrange the groups in a way that the students in the robot could also take part in the circle…*

In contrast, Ethical and Cybersecurity Considerations (E) emerged as a dominant concern primarily among in-class students (n = 18), while remaining marginal for teachers (n = 1) and TPR-mediated students (n = 2). This discrepancy indicates that ethical awareness is shaped by physical co-presence, with in-class students being more attentive to issues of visibility, privacy, and data security.

This concern is illustrated by a student's question:

> *How well can the fellow students hear and see what is actually going on in the class?*

The dimension of Pedagogical Integration (P) is strongly represented among both teachers (n = 27) and TPR-mediated students (n = 26) but less so among in-class students (n = 8). This pattern reflects the dual nature of pedagogy as both a design and an experienced structure. Teachers actively construct pedagogical processes, while TPR-mediated students directly experience their effectiveness.

The importance of pedagogical preparedness is evident in the following student reflection:

> *… the teacher seemed completely overloaded … they didn't know how to divide their attention or what to do when a problem occurred.*

A similar asymmetry is observed in Cognitive and Physical Limitations (C), which are particularly prominent among TPR-mediated students (n = 35), compared to teachers (n = 6) and in-class students (n = 8). This finding indicates that remote participation introduces additional cognitive demands related to managing technological interfaces, interpreting limited non-verbal cues, and maintaining attention in a mediated environment. These constraints are largely invisible to co-present participants, reinforcing the unequal distribution of participation effort across stakeholder groups.

The dimension of Inclusive Access and Engagement (Ie) is highly represented among both student groups (in-class n = 24; TPR-mediated n = 52), while remaining secondary for teachers (n = 17). This suggests that inclusion is primarily experienced rather than designed: while teachers facilitate participation, its effectiveness is evaluated by students, particularly those engaging remotely.

Instructional Methods (Im) show a notably higher frequency among TPR-mediated students (n = 61), compared to in-class students (n = 13) and teachers (n = 8). This highlights the importance of structured guidance, clarity, and explicit instructional support for remote participants.

The need for clear instructions is also reflected in teacher perspectives:

> *I do think that having five or six clear instructions on where and how to direct or move the assistant would be very helpful.*

The comparative patterns identified in Table 16 are further visualised in Figure 12, which illustrates the distribution of PEPCII dimensions across stakeholder groups and makes visible the asymmetries in how different components are prioritised and experienced.

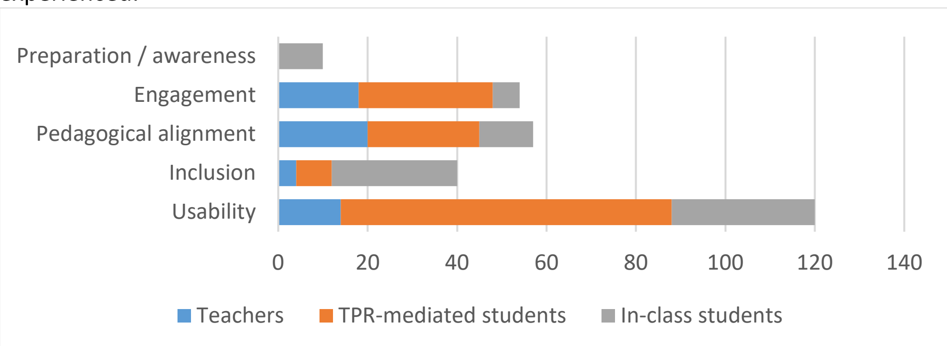

Figure 12. Comparison of PEPCII dimension distributions across stakeholder groups.

Moreover, the validation process can be conceptualised as an iterative refinement loop, as presented in Figure 13. The figure illustrates how insights from teachers, in-class students, and TPR-mediated students contribute to the continuous development and adjustment of pedagogical design.

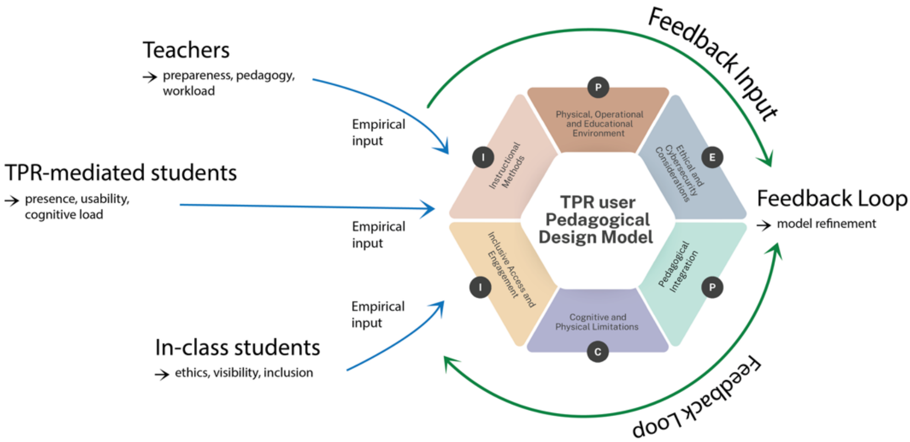

Figure 13. Multi-stakeholder validation and refinement loop of the PEPCII pedagogical design model.

The cross-stakeholder analysis reveals a systematic asymmetry in how the components of the PEPCII model are experienced. While teachers emphasise pedagogical design and structure, and in-class students foreground ethical and inclusion-related concerns, TPR-mediated students experience the learning environment primarily through usability, cognitive load, and instructional clarity. These differences indicate that the effectiveness of the PEPCII model cannot be evaluated from a single perspective but must be understood as an emergent property of interacting stakeholder experiences.

The convergence of empirical evidence across stakeholder groups provides strong support for the structural validity of the PEPCII model. The findings demonstrate that effective implementation of TPR-supported synchronous hybrid learning depends on the balanced integration of environmental, pedagogical, cognitive, ethical, and instructional dimensions, each of which is differently emphasised depending on the stakeholder perspective.

4 Discussion

This chapter interprets the empirical findings presented in Chapter 4 and situates them within the broader research landscape of TPRs in education and hybrid learning design.

4.1 Theoretical Implications

This section discusses the theoretical implications of the thesis by synthesising the findings of Publications I–III in relation to TPRs, synchronous hybrid learning, and technology integration in education. Building on the results presented in Chapter 4, the discussion moves from identifying research fragmentation and pedagogical gaps to the development and empirical validation of the PEPCII model. The findings demonstrate a progression from a fragmented understanding of TPR use in education towards a systematic and pedagogically grounded conceptualisation of TPR integration as a design challenge rather than a matter of technology adoption alone. The following subsections discuss this progression through four stages: the literature-based identification of the problem, the development of the model, its empirical validation, and its broader theoretical contribution.

4.1.1 Telepresence Robots in Education: Insights from a Bibliometric and Thematic Analysis

This subsection discusses the results of the literature review of Publication I, addressing SRQ 1. The analysis of 53 peer-reviewed articles from the Scopus database, conducted using the PRISMA methodology, provides an overview of the current research landscape. The findings indicate that research on TPRs in education is characterised by a growing yet fragmented knowledge base. The results highlight both opportunities and challenges associated with TPRs in education. TPRs are increasingly used to enable remote participation in synchronous hybrid learning. However, the pedagogical foundations guiding their use in the learning process remain fragmented and insufficiently theorised.

Bibliometric analysis of the literature shows that from 2011 to 2022, research on TPRs in the field of education has consistently increased, indicating growing interest and investment in this area. Most of the analysed publications were conference papers and of exploratory nature. This suggests that the field of using TPRs in education is still in an early stage of development. Similar observations have been made in previous literature reviews (Velinov et al., 2021; Virkus et al., 2023). It also appeared that, as research in this field is predominantly concentrated in a limited number of countries, it is geographically uneven.

In Publication I, thematic analysis identifies recurring themes related to the TPR use in educational settings. These include active and inclusive participation of remote students, group discussions, collaboration with experts and collaborators, the inclusion of guest speakers, and conducting lessons by TPR-mediated teachers. The main advantage of TPRs is their ability to enable autonomous movement and interactive communication. They create opportunities for remote participants to experience learning in a way that resembles physical presence in a classroom. These findings are consistent with previous research showing that TPRs can improve social presence and create meaningful learning experiences (Cain et al., 2016; Gleason & Greenhow, 2017). However, the TPR use in learning process lacked theoretical or pedagogical frameworks.

An important finding concerns the role of TPRs in supporting inclusive access to education. The literature highlights that TPRs enable students to maintain social and academic connections with the learning environment, particularly in cases where physical attendance is not possible. This contributes to reducing social isolation and strengthening students' sense of belonging and engagement (Fletcher et al., 2023). These findings suggest that TPRs have significant potential to support inclusive and flexible learning environments, especially in the context of increasingly widespread hybrid learning models. However, the inclusive potential of TPRs depends on how their use is pedagogically structured rather than on the technology itself.

Despite these opportunities, the literature consistently highlights technical and organisational challenges associated with implementing TPRs in education. Issues include unstable network connectivity, communication disruptions due to audio or video delays, and difficulties in navigating classroom spaces. Effective TPR use requires considerable technical preparation and institutional support, increasing the workload of teachers and support stuff (Charteris et al., 2022; Fletcher et al., 2023). These challenges indicate that technological functionality alone does not ensure meaningful educational integration.

A critical finding is that TPRs in previous studies have been weakly grounded in pedagogy. The literature frequently highlights positive effects on engagement and presence, while offering limited guidance on how these technologies should be integrated into teaching and learning processes. This pattern suggests that TPRs are predominantly technology-driven rather than pedagogically grounded. As a result, their educational value is often not systematically aligned with learning objectives, limiting their potential impact. This observation aligns with broader educational technology research, which emphasises that effective technology integration requires alignment between technology, pedagogy, and content (Koehler et al., 2014). Without such alignment, TPRs risk becoming disruptive elements in the learning process.

These findings underline the need for a systematic pedagogical approach integrating TPRs in educational practice. As illustrated in Table 17, the literature reviewed in this study points to several interconnected dimensions influencing TPR use in education, including the physical and operational learning environment, ethical considerations, pedagogical integration, cognitive and physical user limitations, inclusive participation, and instructional methods. While previous studies have addressed these aspects individually, they are rarely considered within a unified pedagogical design framework.

Table 17. Alignment of key literature with the PEPCII pedagogical design dimensions.

PEPCII component	*Core theoretical and empirical foundations*	*Supporting and contextual literature*
Physical, Operational, and Educational Environment (P)	*(Cha et al., 2017; Häfner et al., 2023; Newhart & Olson, 2017; Velinov et al., 2021)*	*(Capello et al., 2022; Leoste et al., 2022; Perifanou et al., 2022; Tota & Vaida, 2020a, 2020b)*
Ethical and Cybersecurity Considerations (E)	*(Charteris et al., 2022; Han & Conti, 2020; Sharkey, 2016)*	*(Davis, 1989; Lei et al., 2022; Venkatesh et al., 2003; Virkus et al., 2023)*
Pedagogical Integration (P)	*(Cain et al., 2016; Gleason & Greenhow, 2017; Koehler et al., 2014; Liao et al., 2022)*	*(Hamilton et al., 2016; Han & Conti, 2020; Moersch, 1995)*
Cognitive and Physical Limitations (C)	*(Cha et al., 2017; Fitter et al., 2020; Jakonen & Jauni, 2022)*	*(Tanaka et al., 2013; Zhang et al., 2018)*
Inclusive Access and Engagement (I)	*(Ahumada-Newhart & Olson, 2019; Fletcher et al., 2023; Lei et al., 2022; Weibel et al., 2020)*	*(Jadhav et al., 2018; Powell et al., 2021; Schmucker et al., 2020; Virkus et al., 2023)*
Instructional Methods (I)	*(Capello et al., 2022; Liao et al., 2022; Maxwell et al., 2017; Molloy et al., 2016; Mudd et al., 2020)*	*Tanaka et al. (2013); Yun et al. (2013)*

Consequently, teachers often lack clear guidance on integrating TPRs into teaching and learning processes. Addressing this gap requires a pedagogically grounded framework that systematically integrates the identified dimensions. This study demonstrates that, although TPRs offer significant potential for enhancing access, social presence, and engagement in hybrid learning environments, their effective adoption is constrained by the absence of integrated pedagogical frameworks. This gap highlights the need for a structured, multidimensional approach that connects technological, pedagogical, social, and ethical considerations. Addressing this need forms the foundation for the development of the PEPCII pedagogical design model, presented in Figure 9, and elaborated in the following subsections. These findings not only reveal the limitations of current approaches but also define the design requirements for a pedagogically grounded framework, which are addressed in the development of the PEPCII model discussed in the next subsection.

4.1.2 Development of the PEPCII Pedagogical Design Model for Telepresence Robots

Following the findings of SRQ1, which revealed the TPR use in the educational context is fragmented and often activity-based, this subsection discusses how the PEPCII model provides a systematic response to these limitations. The findings suggest that a key challenge in the TPR use in synchronous hybrid learning lies in the lack of coherent pedagogical design, particularly in the limited application of established instructional frameworks and pedagogical design models. This gap indicates a misalignment between technological affordances and pedagogical intentions, which may result in uneven and less coherent learning experiences. From the perspective of constructive alignment and technology integration theories (e.g. TPACK), such misalignment constrains the pedagogical effectiveness of TPRs and limits the realisation of their potential for meaningful technology-enhanced learning. The PEPCII model addresses this gap by systematically integrating environmental, cognitive, ethical, and instructional dimensions, ensuring that each aspect is considered in relation to the others to create a cohesive and effective learning framework. While prior research has demonstrated the potential of TPRs to enhance social presence and access, it has largely approached implementation as a technical or situational issue rather than as a systemic pedagogical problem (Ahumada-Newhart & Olson, 2019; Page et al., 2021; Perifanou, 2023). This study argues that effective TPR integration requires a shift from technology-centred adoption towards coordinated pedagogical design, as conceptualised in the PEPCII model, although the PEPCII model incorporates technological and organisational dimensions as enabling conditions for teaching and learning, rather than independent organisational objectives. Consequently, the PEPCII model is positioned as a pedagogical design model for TPR integration.

The robustness of these findings is strengthened through the integration of diverse empirical perspectives. Triangulation was achieved by combining teacher interviews, student reflections, and participatory workshops, enabling validation of findings across multiple viewpoints. Teachers' experiences revealed that TPR integration is shaped by environmental and organisational conditions, including infrastructure, institutional support, and pedagogical readiness. Students' experiences demonstrated that access alone does not ensure meaningful participation, emphasising the role of social presence, cognitive load, and interactional awareness. Participatory professional workshops with co-creation elements translated these insights into actionable design principles, highlighting the need for structured interaction protocols and clearly defined roles. This multi-phase, iterative design-based approach ensured that the PEPCII model was progressively refined through cycles of testing and revision.

The six components of the PEPCII model (Table 18), which include environmental, cognitive, ethical, instructional, social, and technological dimensions, are deeply interconnected. For example, in a synchronous hybrid lesson using a TPR, the physical and technical environment (e.g. classroom layout, audio-visual quality) directly shapes students' ability to interact. Poor audio or limited visibility can increase cognitive load, making it difficult for remote students to follow discussions and participate meaningfully. To address this, instructional methods such as structured turn-taking or clearly defined interaction protocols can be introduced. At the same time, ethical considerations, such as managing camera visibility and ensuring students' comfort, influence how interaction is designed. This shows how changes in one dimension (e.g. environment) cascade across cognitive, instructional, and ethical dimensions, ultimately affecting student engagement and participation. This interconnectedness creates a dynamic system in which changes in one component influence the others. Environmental conditions shape pedagogical integration, while cognitive load and accessibility influence students' participation. Ethical considerations such as visibility and privacy are closely linked to instructional decisions.

Table 18. Pedagogical implications of the PEPCII model dimensions for synchronous hybrid learning.

PEPCII model dimension	*Description*	*Pedagogical relevance*	*Design implications for TPR-mediated courses*
Physical, operational, and educational environment	*Classroom layout, TPR positioning, and technical setup enabling hybrid participation*	*Determines remote students' visibility, mobility, and interaction*	*Plan robot placement, visibility, and spatial configuration to support communication and participation*
Ethical and cybersecurity considerations	*Privacy, responsible use, and data protection*	*Ensures safe, appropriate, and compliant participation*	*Establish clear rules for camera use, recording, and data handling*
Pedagogical integration	*Alignment of TPR use with learning goals, tasks, and teaching approaches*	*Enables meaningful use beyond technical add-on*	*Integrate TPR use into learning outcomes and course activities*
Cognitive and physical limitations	*Cognitive load, accessibility, and operational demands*	*Supports inclusion and reduces participation barriers*	*Structure tasks clearly and account for accessibility and usability needs*
Inclusive access and engagement	*Opportunities for all students to participate and interact*	*Prevents passive or marginalised participation*	*Design activities that ensure equitable interaction and collaboration*
Instructional methods	*Preparation, guidance, training, and implementation support TPR-mediated participation*	*Supports confident, effective, and sustainable participation by teachers and students*	*Provide onboarding, demonstrations, rehearsal opportunities, technical support, FAQs, and participation guidelines*

The PEPCII model stresses the interdependence of its dimensions, with effective TPR-supported hybrid learning emerging from the dynamic interaction between environmental, pedagogical, cognitive, ethical, and instructional factors. The effectiveness of instructional support and preparation practices is influenced by the physical and technical environment, while students' engagement is shaped by cognitive load, social presence, and pedagogical structuring. Ethical considerations such as visibility and privacy directly influence instructional practices, requiring teachers to design activities that ensure students' agency, comfort, and trust in participating through TPRs. This interconnectedness shows that the PEPCII model functions as a coordinated system, where changes in one dimension affect the effectiveness of others. Figure 14 illustrates this systemic perspective by visualising how these dimensions interact and jointly shape meaningful participation in synchronous hybrid learning environments.

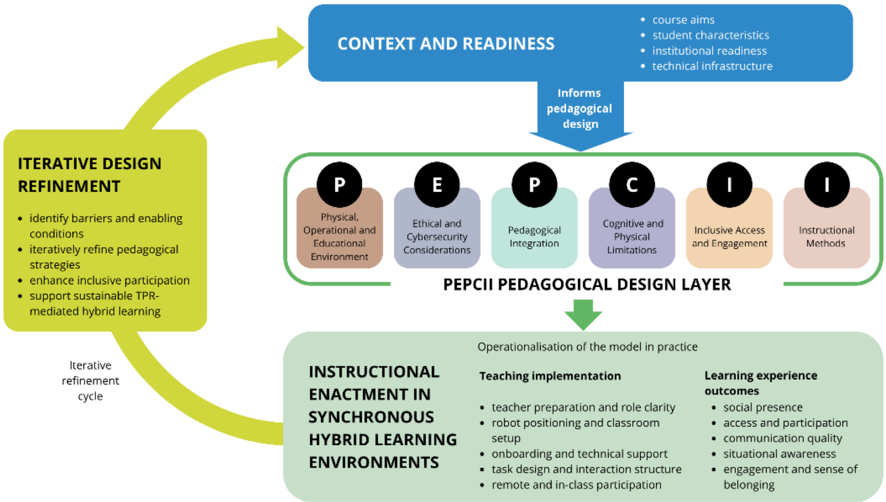

Figure 14. Hybrid learning design informed by the PEPCII model.

Unlike existing frameworks that isolate technological, pedagogical, or communicative aspects, the PEPCII model conceptualises TPR integration as a relational and context-dependent process, emphasising dynamic interaction between environmental, cognitive, ethical, and instructional dimensions in practice. This approach illuminates the interaction of these dimensions in practice, offering a more holistic understanding than models like TRinE 4D (Perifanou, 2023) and the 4C framework (Chan, 2024), which provide valuable insights into hybrid learning but do not sufficiently address how these dimensions interact in practice. While TPACK (Mishra & Koehler, 2006) integrates knowledge domains, it does not explicitly account for environmental, organisational, and ethical constraints that shape real-world implementation. The PEPCII model extends these approaches by positioning hybrid learning as a coordinated system where environmental, cognitive, pedagogical, and ethical factors are intertwined.

This systemic perspective addresses limitations identified in some prior research, such as the oversight of visibility, privacy, and data security, which can lead to student discomfort and reluctance to participate in TPR-mediated environments. By incorporating these factors into pedagogical design, the model ensures student agency and trust. Existing models often overlook how visibility, privacy, and data security shape participation in TPR-mediated environments. Cognitive load and embodied interaction demand remain underexplored, despite their direct impact on students' ability to engage meaningfully through telepresence technologies. The PEPCII model incorporates these dimensions into pedagogical design, emphasising that participation emerges from the coordination of attention, interaction, and movement in hybrid learning contexts. The model advances existing notions of inclusion by distinguishing between access and meaningful engagement. The findings demonstrate that access to technology alone does not guarantee meaningful involvement – that depends on social presence, interactional structures, and pedagogically guided support. This reframes inclusion as an actively designed pedagogical process rather than a purely technical condition.

These findings provide a clear response to SRQ2: the PEPCII model supports TPR adoption by reconceptualising it as a systemic, context-dependent design problem. This perspective shifts the focus from individual technology use or functional adoption towards the intentional design of learning environments that support interaction, inclusion, and engagement.

The findings suggest that the educational value of TPRs is realised only when supported by deliberately designed pedagogical practices, including structured learning activities and clearly defined interaction protocols.

4.1.3 Empirical Validation of the PEPCII Model in Higher Education

This subsection addresses SRQ3 by examining the empirical validation of the PEPCII model in higher education. The findings indicate that the PEPCII model is empirically validated in terms of practical applicability as a context-sensitive and operational pedagogical design framework for TPR-mediated synchronous hybrid learning in higher education. The findings of Publication III support the relevance of the model's components and demonstrate its value as a pedagogically grounded and operational design framework for TPR-supported hybrid learning.

The validation represents a transition from conceptual formulation to empirical operationalisation in higher education, as the model was enacted across course design, instructional practices, and teacher training contexts. Initially developed to conceptualise the pedagogical, environmental, ethical, cognitive, and inclusion-related dimensions for integrating TPR learning, the findings indicate that these dimensions can function as an actionable framework within authentic educational settings. However, this applicability is contingent upon specific pedagogical and institutional conditions, including the availability of technical support, teacher preparedness, and appropriately configured learning environments. Rather than evidencing universal generalisability, the validation demonstrates context-bound utility in supporting the design and implementation of synchronous hybrid learning with TPRs. This outcome aligns with the principles of design-based research, wherein models are iteratively refined through situated application rather than treated as stable, universally valid solutions. Furthermore, the findings suggest that the model can inform instructional design through structuring learning activities, facilitating engagement, and managing cognitive load, while its effectiveness remains dependent on context-sensitive enactment shaped by teacher expertise, student readiness, and infrastructural capacity.

Building on its validation, this practical operationalisation underscores the PEPCII model's unique contribution to existing technology integration frameworks. While TAM, UTAUT, and TPACK provide important foundations for understanding technology adoption and integration, they provide limited guidance for addressing the situated and multidimensional nature of TPR-mediated hybrid learning. The validation suggests that the PEPCII model addresses these conditions more explicitly in the context of TPR-mediated hybrid learning by framing them as interconnected dimensions. At the same time, this does not imply that existing frameworks are insufficient per se, but rather that they require complementary perspectives when applied to embodied and socially situated technologies such as TPRs.

A central implication of the validation is that these dimensions are more appropriately understood as pedagogical design conditions than isolated implementation factors. This distinction is important because it reframes technical, ethical, cognitive, and organisational issues from peripheral constraints into constitutive elements of instructional design. As a result, effective TPR use in educational context is understood not as a matter of technology deployment alone but as the deliberate design of conditions that enable meaningful participation, interaction, and inclusion. Earlier research indicates that meaningful TPR-mediated participation depends on reliable connectivity, classroom configuration, teacher preparation, technical support, and inclusive interaction practices (Capello et al., 2022; Liao & Lu, 2018; Okundaye et al., 2020; Powell et al., 2021; Spoden & Ema, 2024). Furthermore, prior studies highlight that insufficient pedagogical guidance, limited situational awareness, and weak support structures may increase cognitive load and reduce engagement (Asadi & Fischer, 2025; Nordtug & Johannessen, 2023; Rode et al., 2024; Weibel et al., 2024). The findings of this thesis align with these observations but also extend them by highlighting that such factors operate as interdependent conditions shaping the possibility of meaningful participation.

A further theoretical strength of the validation lies in its multi-stakeholder perspective. By examining the model through the perspectives of teachers, TPR-mediated students, and in-class students, the findings suggest that TPR-supported hybrid learning is inherently relational and cannot be adequately understood from a single-user perspective. However, the relative emphasis of different perspectives may also reflect specific study contexts and participant roles. While the triangulation strengthens the explanatory scope of the model, further research would be needed to examine whether similar role-sensitive patterns emerge across different institutional and disciplinary settings.

The role-sensitive pattern identified in the findings indicates that different dimensions become salient depending on participants' positionality. Teachers foreground issues related to pedagogical integration and instructional guidance, TPR-mediated students emphasise access, inclusion, cognitive load, and operational conditions, while in-class students highlight ethical and social aspects such as visibility and recognition. While this distribution supports the internal coherence of the PEPCII model, it also suggests that the relative importance of its components may shift across contexts and cannot be universally prioritised.

In summary, the validation helps address the fragmentation identified in the literature, illustrating that TPR-supported hybrid learning can be cohesively conceptualised through an operational pedagogical framework. Unlike earlier research, which examined individual aspects of TPR use in isolation, the findings show that meaningful participation emerges from deliberate coordination of interdependent conditions, not technological adoption alone. The PEPCII model reframes TPR integration as a pedagogical design problem, providing a structured response to the lack of systematic guidance in previous research.

The validation did not require conceptual reconstruction of the PEPCII model but resulted in component-level refinement that enhanced its operational applicability. Rather than altering the overall structure, the validation clarified how the model can be enacted in practice, for example through activity-based spatial planning, clearer consent and visibility protocols, more proactive participation strategies, and systematic support for managing cognitive load during TPR-mediated participation. These refinements are synthesised in Table 19, which illustrates how the conceptual components of the PEPCII model were translated into operational design conditions through empirical validation.

Table 19. From conceptual dimensions to operational design conditions in the PEPCII model.

PEPCII component	*Conceptual dimension (before validation)*	*Empirical refinement*	*Operational design condition*
Physical, Operational, and Educational Environment	*General infrastructure readiness and classroom suitability for TPR use*	*Activity-specific spatial design, robot positioning, movement paths, audio zoning, and mandatory pre-class environmental testing*	*Learning environments must be deliberately configured for each activity, including spatial layout, visibility, and technical conditions.*
Ethical and Cybersecurity Considerations	*Ethics and cybersecurity addressed as general principles and compliance issues*	*Explicit interaction-level protocols for consent, camera visibility, observation boundaries, and shared responsibility*	*Ethical TPRs use requires clearly defined and enacted protocols for consent, visibility, and responsibility.*
Pedagogical Integration	*Alignment of TPR use with learning outcomes and teaching strategies*	*Deliberate interaction design: structured turn-taking, role assignment, and explicit inclusion of TPR-mediated students*	*Pedagogical integration must be actively designed through structured interaction and facilitation strategies.*
Cognitive and Physical Limitations	*User-related cognitive and physical constraints inherent to TPR technology*	*Cognitive load management through task sequencing, simplified interfaces, and control protocols*	*Cognitive load must be actively managed through task design, sequencing, and interface simplification.*
Inclusive Access and Engagement	*Telepresence assumed to provide access and inclusion*	*Clear distinction between access and inclusion, supported by active participation strategies*	*Inclusion requires intentional design that ensures visibility, recognition, and active participation.*
Instructional Methods	*Broad instructional guidance without differentiation by experience level*	*Stage-appropriate methods and continuous professional development*	*Instructional approaches should be adapted to experience level and supported through ongoing development.*

The validation addresses the fragmentation identified in the literature and demonstrates that TPR-supported hybrid learning can be cohesively conceptualised through an operational pedagogical framework. Unlike earlier research, which examined individual aspects of TPR use in isolation, the findings show that meaningful participation emerges from the deliberate coordination of interdependent conditions rather than from technological adoption alone.

In response to SRQ3, the findings confirm that the PEPCII model is not only theoretically grounded but also empirically validated in terms of its applicability as a practical design framework that supports the implementation of TPR-mediated synchronous hybrid learning in higher education.

Findings across Publications I–III demonstrate a clear progression from a fragmented research field towards a coherent and operational understanding of TPR-mediated hybrid learning. While the literature revealed a lack of systematic guidance for integrating TPRs into educational practice (SRQ1), and the PEPCII model provided a theoretically grounded response to this gap (SRQ2), the validation shows how this framework can be enacted in authentic higher education contexts (SRQ3). This positions TPR-supported hybrid learning as a pedagogical design challenge requiring coordinated, context-sensitive, and inclusive approaches.

Importantly, this is particularly relevant for inclusive and equitable participation, as the model demonstrates how pedagogical design can support not only access but also meaningful engagement and well-being for all participants. Such participation depends on institutional support, pedagogical training, and context-sensitive implementation, highlighting the PEPCII model's role as both an analytical framework and a practical guide for structuring TPR-supported learning activities.

4.2 Practical Implications

This section discusses the practical implications of the thesis by considering how the findings can inform the implementation of TPRs in synchronous hybrid learning. While previous research has highlighted the potential of TPRs to enhance social presence, access, and inclusion, the findings of this thesis show that these outcomes do not emerge from technology use alone. Rather, successful TPR use in learning depends on systematic pedagogical design, context-sensitive implementation, and coordinated institutional support. In this respect, the PEPCII model provides a practical framework for teachers, students, and institutional stakeholders by translating key pedagogical, environmental, ethical, cognitive, and inclusion-related dimensions into actionable design considerations. Building on these insights, the following subsections discuss the implications of the model for hybrid learning design, teacher training, and institutional implementation.

4.2.1 Implications for Hybrid Learning Design

For the design of synchronous hybrid learning, the PEPCII model provides a concrete framework for planning learning environments in which both remote and in-class participants can engage meaningfully. Introducing TPRs into teaching requires more than simply providing technological access; it requires careful attention to how classroom space, communication, participation structures, and learning tasks are organised. This means that the design of TPR-mediated learning must account for the affordances and limitations of the environment in which participation takes place.

A key implication of the findings is that meaningful involvement depends not only on whether remote participants can technically hear and see classroom activities through the robot's audio and video functions, but also on whether interaction is deliberately structured. Empirical findings across the thesis indicate that low audio quality, limited visual access, unclear communication protocols, and poorly coordinated interaction can significantly hinder participation and collaboration. As a result, hybrid learning design must include an explicit consideration of how remote participants will communicate, move, collaborate, and take part in shared learning activities.

The PEPCII model supports teachers in designing such learning environments by foregrounding several practical considerations. First, both the physical and digital learning environments need to be organised to support equitable participation. This includes classroom layout, robot positioning, visibility, screen placement, and the use of additional communication channels where needed. Second, interaction needs to be pedagogically structured through guided discussions, collaborative group work, role allocation, and clear participation protocols that connect remote and in-class students in purposeful ways. Third, the design of learning activities should take account of cognitive load, particularly for remote participants who must simultaneously navigate the robot, follow classroom events, and engage through multiple communication channels.

An important practical implication is that TPR-mediated participants should not be positioned as passive observers but as active participants in the learning process. This requires inclusive task design, clear opportunities for contribution, and instructional methods that support engagement across modalities. In this sense, the PEPCII model functions as a practical guide for designing hybrid learning environments in which TPR use is aligned with pedagogical aims rather than added as an isolated technical feature.

4.2.2 Implications for Teacher Training

The findings highlight that effective TPR integration requires more than technical competence. It also requires pedagogical preparedness, the ability to adapt to hybrid learning environments, and the capacity to manage interaction across physically and remotely present participants. Teachers in a classroom where TPR is integrated with synchronous hybrid learning often must juggle multiple demands simultaneously, including facilitating discussion, monitoring participation, resolving technical issues, and ensuring that remote students are meaningfully engaged in class activities. Or, if the class is being conducted by a TPR-mediated teacher, they must ensure that the necessary teacher presence is provided.

The analysis suggests that teachers benefit from structured preparation that goes beyond learning how to operate the technology. Opportunities to experiment with TPRs, reflect on their use, and develop strategies for handling challenges such as communication breakdowns, reduced non-verbal cues, and uneven participation are especially important. Without such preparation, TPR use may increase teachers' cognitive load and disrupt the flow of teaching rather than support it.

From the perspective of the PEPCII model, teacher training should focus on several interconnected areas. First, it should develop teachers' pedagogical strategies for hybrid interaction, including how to engage remote students, balance attention between participant groups, and structure inclusive learning activities. Second, it should help teachers understand the communicative limitations of TPR-mediated participation, such as delayed responses, restricted body language, and limited situational awareness, and support them in compensating for these constraints through instructional design. Third, training should address classroom management in hybrid settings, including coordination with assistants or support staff and strategies for responding to technical disruptions without undermining the learning process.

In addition, teacher training should raise awareness of ethical and cybersecurity issues, including data privacy, responsible use of cameras and recording functions, and the importance of secure communication channels. This is especially relevant in TPR-mediated learning, where visibility, presence, and observation are not only technical but also pedagogical and ethical issues.

Professional development should therefore be iterative and practice-based rather than limited to one-off technical induction sessions. Activities such as mock hybrid classes, peer collaboration, guided experimentation, and reflective teaching practice can support the gradual development of confidence and competence. This aligns with the broader finding of the thesis that TPR-supported teaching should be understood as an evolving pedagogical practice rather than a fixed set of technical skills.

4.2.3 Implications for Institutional Implementation of TPRs

At the institutional level, the findings emphasise that successful TPR integration requires systemic support structures rather than isolated technology adoption. Although TPRs may be introduced as innovative tools for synchronous hybrid learning, their effective use depends on coordinated organisational, technical, and pedagogical conditions. In other words, institutions cannot assume that the provision of robots alone will lead to meaningful educational use.

The studies show that support mechanisms such as technical assistance, teacher training, infrastructure planning, and pedagogical guidance are critical for enabling teachers to focus on teaching rather than troubleshooting technology. Without such support, responsibility for implementation is shifted onto individual teachers, which may reduce teaching quality and negatively affect the student experience.

The PEPCII model has clear practical implications for institutional implementation. Institutions need to ensure reliable infrastructure, including stable internet connectivity, appropriate classroom configurations, and high-quality audio-visual conditions that support robot-mediated participation. They also need to provide both technical and pedagogical support, for example through on-site assistants, instructional design expertise, and access to training opportunities. Clear institutional policies are also required, particularly concerning ethical use, privacy, consent, visibility, and cybersecurity.

Another important implication concerns inclusive access. Institutions should not view TPRs merely as accessibility devices that allow remote attendance but as part of a broader strategy for enabling meaningful participation for students who cannot be physically present. This requires planning for interaction, recognition, and engagement, rather than only for connection and access.

Finally, the findings indicate that TPR implementation should be understood as an ongoing institutional process rather than a one-time technological investment. Sustainable implementation depends on alignment between pedagogy, technology, organisational routines, and professional development. From this perspective, the PEPCII model offers institutions not only an analytical framework for understanding TPR-supported hybrid learning but also a practical guide for developing the conditions under which such learning can be implemented in a coherent, inclusive, and pedagogically meaningful way.

The practical implications of the PEPCII model can be synthesised across different implementation levels, illustrating how its dimensions translate into actionable design considerations for hybrid learning environments, teacher practices, and institutional support structures (see Table 20).

Table 20. Operational implications of the PEPCII model across implementation level.

PEPCII dimension	*Hybrid learning design (course level)*	*Teacher practice*	*Institutional support*
Physical, Operational, and Educational Environment	*Plan classroom layout, visibility, and audio conditions for TPR participation*	*Manage spatial setup and robot use during sessions*	*Provide reliable infrastructure and technical support*
Ethical and Cybersecurity Considerations	*Define participation, visibility, and camera-use norms*	*Apply consent, privacy, and responsible use practices*	*Establish policies for data protection and ethical use*
Pedagogical Integration	*Design structured, interactive activities with TPR inclusion*	*Facilitate participation and connect remote and in-class students*	*Support pedagogical design and guidance*
Cognitive and Physical Limitations	*Simplify tasks and reduce multitasking demands*	*Monitor and manage students' cognitive load*	*Ensure accessible tools and usability support*
Inclusive Access and Engagement	*Design for active participation, not just access*	*Engage remote students and balance participation*	*Promote inclusive participation strategies*
Instructional Methods	*Use collaborative and discussion-based methods*	*Apply adaptive and interactive teaching strategies*	*Support training and sharing of best practices*

The practical implications of this thesis demonstrate that the effective TPR use in synchronous hybrid learning requires coordinated action across multiple levels of educational practice. As summarised in Table 20, the PEPCII model translates into concrete design actions at the level of learning environments, teacher practices, and institutional support structures. These findings reinforce the central argument of this thesis: that TPR integration cannot be understood as a matter of technological adoption alone but must be approached as a systemic pedagogical design process.

From a practical perspective, this means that meaningful participation in TPR-mediated learning emerges not from access to technology itself but from the deliberate alignment of environmental conditions, pedagogical structuring, interaction design, and institutional support. The PEPCII model therefore provides not only a conceptual framework but also a practical tool for guiding the design and implementation of inclusive and pedagogically coherent hybrid learning environments. By operationalising these dimensions into actionable strategies, the model supports educators and institutions in moving beyond ad hoc TPR use towards more intentional, sustainable, and context-sensitive practices in higher education.

5 Conclusion

This chapter concludes the thesis by synthesising the main findings and contributions of the study and reflecting on their implications for research and practice. Building on the discussion presented in Chapter 5, this chapter brings together the results of Publications I–III and revisits the research questions considering the developed and empirically validated PEPCII model. The chapter begins by summarising the main findings of the thesis in relation to the research questions, highlighting the progression from a fragmented understanding of telepresence robot (TPR) use in education towards a coherent and pedagogically grounded design framework for synchronous hybrid learning. It then outlines the theoretical and practical contributions of the study, emphasising how the PEPCII model advances both conceptual understanding and real-world implementation of TPRs in the learning.

Following this, the chapter discusses the limitations of the research and identifies directions for future studies, particularly in relation to the transferability, scalability, and continued development of the model. The chapter concludes by reflecting on the broader implications of the findings for the field of technology-enhanced learning and the future design of inclusive hybrid learning environments.

5.1 Summary of Main Findings

This thesis examines what framework guides TPR integration in synchronous hybrid learning environments. The findings show that TPR integration demands a comprehensive pedagogical design model addressing broader conditions shaping participation, interaction, inclusion, and engagement.

The PEPCII model that was developed and validated during this study provides such a framework by integrating six interrelated dimensions. These dimensions guide the design, implementation, and evaluation of TPR use in learning and teaching, supporting inclusive and sustainable learning environments for both remote and on-class participants. These dimensions guide the design, implementation, and evaluation of TPR use in a synchronous hybrid. Furthermore, supporting inclusive and sustainable learning environments for both remote and on-class participants, the PEPCII model integrates TPRs as integral elements of the learning environment, not isolated tools. It addresses pedagogical, technological, environmental, ethical, cognitive, and inclusion-related factors to enable remote students to navigate classroom environment, participate in learning activities, and interact with teachers and peers in real time. TPRs support meaningful participation, strengthen social presence through embodied interaction, and promote pedagogical coherence between in-class and remote students.

The empirical findings across all three research phases demonstrate that effective TPR integration is characterised by:

(1) purposeful pedagogical orchestration, where learning activities, roles, and interaction patterns are explicitly designed to include both remote and in-class participants.

(2) environmental and organisational preparedness, ensuring that technical infrastructure, spatial arrangements, and support roles enable seamless participation.

(3) cognitive and interactional alignment, where the design of tasks and tools reduces cognitive load and supports active and interactive learning.

(4) ethical and inclusive implementation, safeguarding privacy, ensuring equitable participation, and promoting a psychologically safe learning environment; and
(5) instructional adaptability, allowing teachers to flexibly apply teaching methods that leverage the embodied and mobile nature of TPR-mediated presence.

The findings from the three research phases formed a coherent progression. The systematic literature review identified the pedagogical opportunities, challenges, educational scenarios, and didactical methods associated with TPR use in education. These findings informed the development of the PEPCII model, which was subsequently refined through empirical studies involving teachers and students and later validated in authentic higher education settings. Together, these phases provided the conceptual, empirical, and practical foundations for the PEPCII model.

The multi-phase development and validation process further demonstrated a high level of operational readiness of the PEPCII model. Within the studied higher education contexts, the findings indicate that the model achieved a level of maturity corresponding to Technology Readiness Level 9, reflecting its stable and sustained use in authentic educational settings.

In contrast to existing approaches, which predominantly treat TPR use as a technical or situational challenge, the PEPCII model conceptualises integration as a pedagogical design problem. The main contribution of the thesis lies in identifying and validating the PEPCII model as an effective pedagogical design model, demonstrating that successful TPR integration depends on the deliberate coordination of technological affordances with pedagogical intent, rather than on the technology itself. The PEPCII model provides a structured yet adaptable architecture that connects theoretical principles, empirical evidence, and practical implementation conditions. The findings further demonstrate that successful TPR integration depends not only on pedagogical design decisions but also on organisational readiness. Effective implementation requires appropriate infrastructure, technical and pedagogical support systems, teacher preparation, and institutional practices that enable the sustainable TPRs use within educational settings. This enables teachers and institutions to systematically design synchronous hybrid learning environments in which TPR-mediated participation becomes pedagogically meaningful, inclusive, and sustainable.

5.2 Contributions of the Thesis

This thesis contributes to the field of technology-enhanced learning by advancing the understanding of how TPRs can be meaningfully integrated into synchronous hybrid learning environments. The contribution is both theoretical and practical, addressing a key gap in existing research related to the lack of pedagogically grounded frameworks for TPR use in education.

From a theoretical perspective, the thesis reconceptualises TPR integration as a pedagogical design problem, not just a matter of technology adoption. Meaningful TPR use in learning where students or teachers are mediate by TPR requires coordinated interaction between environmental conditions, pedagogical structuring, cognitive load, ethics, inclusion, and instructional methods. The PEPCII model contributes to theory by integrating necessary previously described dimensions into a systemic framework, thereby addressing fragmentation in previous literature. It shifts focus from individual use and acceptance to designing learning conditions that enable participation, interaction, and inclusion.

The thesis provides a practical framework for implementing TPRs in real-world educational settings. The PEPCII model breaks down complex pedagogy and context into actionable elements: hybrid learning design, teacher practices, and organisational support. The effectiveness of the PEPCII model was confirmed through a validation process conducted in a real higher education context, which revealed key conditions for the successful functioning of the model. Validation confirmed the model's effectiveness, revealing key conditions for success: structured interaction, environmental configuration, cognitive load management, and inclusive participation strategies. This framework offers educators and institutions a methodical way to move beyond ad hoc or technology-driven approaches and adopt more grounded practices.

Importantly, the findings also contribute by identifying the conditions under which TPR integration may be scalable and sustainable. While the thesis does not empirically test scalability across diverse institutional contexts, it outlines the organisational, pedagogical, and infrastructural requirements that support the transferability of the model. This positions the PEPCII model not only as an analytical framework but also as a foundation for future development and implementation of TPR-supported hybrid learning in higher education.

As shown in Publication II, the validation process progressed from implementation in authentic higher education settings (TRL 7) to multi-stakeholder validation (TRL 8) and sustained pedagogical functioning across courses and contexts (TRL 9), indicating the operational readiness of the PEPCII model.

The thesis contributes a theoretically grounded and empirically informed framework that advances both the conceptual understanding and practical implementation of TPR in learning. By bridging the gap between technology adoption and pedagogical design, it provides a new lens for understanding how hybrid learning environments can be created to support meaningful, inclusive, and sustainable participation.

5.3 Limitations and Future Research

This thesis has several limitations that should be considered when interpreting the findings and considering the applicability of the PEPCII model. These limitations relate primarily to the contextual scope of the empirical studies, the characteristics of the participant groups, the nature of the evidence collected, and the still-evolving role of TPRs in synchronous hybrid learning.

First, the empirical studies were conducted in specific higher education contexts and within relatively restricted institutional settings. This inevitably limits the generalisability of the findings across other educational levels, disciplinary domains, and institutional environments. However, this is consistent with the design-based research approach adopted in the thesis, which aims to generate context-sensitive and iteratively refined design knowledge rather than universally generalisable solutions. The findings should therefore be understood as providing a grounded and practice-oriented framework for the pedagogical design of TPR use in synchronous hybrid learning rather than a universally applicable model. This contextual limitation is also reflected in the development and validation studies reported in the core publications of the thesis.

Second, the thesis focuses specifically on synchronous hybrid learning supported by TPRs. Because TPRs combine remote participation with mobility, embodiment, and socially visible presence, they differ in important ways from conventional videoconferencing and other online learning arrangements. While the PEPCII model offers insight into the pedagogical integration of embodied hybrid participation, its applicability to other forms of hybrid or online learning remains to be established. Further research is therefore needed to determine which aspects of the model are specific to TPR use and which may be transferable to broader technology-mediated learning contexts. This need is in line with the literature review, which identified a lack of dedicated pedagogical frameworks for TPR use in education, as well as with the model-development study, which called for further validation in varied learning settings.

Third, although the thesis incorporates the perspectives of teachers, TPR-mediated students, and in-class students, the participant groups remain relatively limited in scope. The studies provide rich insight into authentic educational practice, but they do not capture the full diversity of possible users, disciplines, or institutional cultures. In addition, some of the participants were drawn from digitally resourceful higher education environments, which may have influenced their readiness to engage with TPR use in learning. It is therefore possible that the relative importance of the PEPCII dimensions would differ in other educational or cultural contexts. Future research should examine the model across larger, more diverse, and more varied participant populations.

Fourth, part of the evidence base relies on self-reported perceptions and reflective accounts rather than direct behavioural observation or objective measures of learning outcomes. This is particularly relevant in relation to participants' experiences of inclusion, interaction, preparedness, and usability. While such evidence is highly valuable for understanding pedagogical implementation and perceived educational quality, it does not by itself establish causal effects on academic performance or longer-term learning outcomes. The thesis therefore provides stronger evidence for the practical usability and pedagogical relevance of the PEPCII model than for its measurable impact on learning achievement.

Fifth, the literature-based foundation of the thesis is itself subject to scope limitations. The review reported in Publication I was restricted to Scopus-indexed studies and selected search terms related to TPRs in education. As a result, relevant work using alternative terminology or published in other databases may not have been captured. The thesis therefore offers a systematic and well-founded, but not exhaustive, overview of the research field.

Sixth, although the thesis identifies key pedagogical, organisational, technical, and ethical conditions for effective implementation, it does not fully examine the long-term scalability and sustainability of TPR use in education. The PEPCII model outlines important requirements for sustained implementation, but further research is needed to investigate how these conditions can be maintained over time and across larger-scale institutional adoption. Questions related to technical support, maintenance, costs, teacher workload, and institutional policy remain particularly important in this regard.

Seven, a deliberate focus of the thesis is on pedagogical and epistemological perspectives of technology integration, primarily drawing on models such as TAM, TPACK, and related frameworks. As a result, organisational theories and models addressing leadership, institutional support, professional development, infrastructure, and quality assurance are not examined in depth. This limitation was introduced to maintain a clear focus on the educational processes underpinning the development of the PEPCII model. Future research could extend this work by investigating the PEPCII model implementation at the organisational level, examining how applicable its dimension for implementing TPRs at institutional structures and leadership practices is.

Finally, the thesis should be read considering the rapidly evolving nature of telepresence and hybrid learning technologies. The PEPCII model was developed in relation to current TPR platforms and contemporary hybrid teaching practices. As these technologies continue to develop, some of the barriers identified here may diminish, while new pedagogical, social, and ethical questions may emerge. The model should therefore be understood as an empirically grounded but evolving framework that remains open to further refinement in response to future technological and educational developments.

These limitations point to several important directions for future research. Longitudinal studies are needed to examine how TPR integration develops over time and how pedagogical practices stabilise through repeated use. Comparative studies across institutions, disciplines, and educational levels would help to assess the transferability of the PEPCII model. Future research should also include larger and more diverse participant groups and combine experiential evidence with observational, behavioural, and performance-based data. In addition, further work is needed to explore how the PEPCII model may be adapted to other technology-mediated learning environments, and how it may interact with emerging developments in embodied and intelligent educational technologies.

These limitations do not diminish the contribution of the thesis. Rather, they clarify its scope and highlight productive opportunities for further research. The thesis provides a theoretically informed and empirically grounded foundation for the pedagogical design of TPR use in synchronous hybrid learning and supports the continued refinement and extension of the PEPCII model in diverse educational contexts.

5.4 Final Concluding Remarks

This thesis has explored the role of TPRs in synchronous hybrid learning by moving beyond a technology-centred perspective towards a pedagogically grounded understanding of their integration in educational practice. The findings demonstrate that the value of TPRs does not lie in their ability to provide access alone, but in how they are embedded within carefully designed learning environments that support interaction, inclusion, and meaningful participation.

By developing and empirically validating the PEPCII model, this study offers a systematic framework for understanding and designing TPR use on learning as a coordinated pedagogical process. The model highlights that participation in hybrid learning environments emerges from the alignment of environmental, pedagogical, cognitive, ethical, and organisational conditions, rather than from the use of technology in isolation. In doing so, the thesis contributes to a broader shift in educational technology research, where the focus moves from adoption and functionality towards the design of learning experiences.

As hybrid learning continues to evolve in higher education, the findings of this thesis suggest that telepresence technologies have the potential to play a meaningful role in supporting inclusive and flexible learning environments. However, realising this potential requires sustained attention to pedagogical design, institutional support, and the lived experiences of students and teachers. The PEPCII model provides a foundation for this work, offering both a conceptual lens and a practical guide for future research and implementation. Furthermore, the thesis demonstrates that pedagogical design models for emerging educational technologies can be developed and evaluated using a readiness-oriented approach. Through iterative development, piloting, and validation in authentic higher education settings, the PEPCII model progressed beyond a conceptual framework and demonstrated operational maturity for practical application within the investigated contexts.

Beyond its contribution to TPR integration, the PEPCII model supports broader educational goals related to inclusion, accessibility, and sustainability. By enabling meaningful participation for students who may be excluded due to health conditions, geographical distance, or other barriers, the model contributes to more equitable access to education. At the same time, the TPR use within well-designed synchronous hybrid learning environments may reduce the need for travel while maintaining social and educational participation. In this way, the findings contribute to ongoing efforts to develop more inclusive, resilient, and sustainable educational systems.

Abbreviations

DBR	Design Based Research
DT	Design Thinking
HEI	Higher Education Institution
ICAP	The Interactive, Constructive, Active, Passive
MRP	Mobile Robotic Telepresence
PEOU	Perceived Ease of Use
PEPCII	Physical, Operational and Educational Environment Ethical and Cybersecurity Considerations Pedagogical Integration Cognitive and Physical Limitations Inclusive Access and Engagement Instructional Methods
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PU	Perceived Usefulness
SCOPUS	Database used for the systematic review
SDG	Sustainable Development Goals
SQR	Sub-Research Question
TAM	Technology Acceptance Model
TPACK	Technological Pedagogical Content Knowledge
TPR	Telepresence Robot
TRL	Technology Readiness Level
UTAUT	Unified Theory of Acceptance and Use of Technology
WWW	World Wide Web

Explanations of abbreviations used in the thesis.

Glossary

Accessibility	The extent to which educational opportunities, learning environments, and technologies are designed to enable participation and learning for all students, regardless of their health condition, location, disability, or other individual needs.
Agency	The student's ability to act purposefully, make choices, and influence the course of their learning activities and environment.
Autonomy	The student's independence in the learning process, including the ability to plan, regulate, and evaluate their own learning.
Cognitive and Physical Limitations (C)	The cognitive, physical, and technological constraints that may influence participation, communication, learning, and user well-being in TPR-mediated environments.
Cognitive load	The load on working memory during learning activities.
Co-presence	The perceived being-together with other participants in the same (physical or virtual) learning environment.
Digital education	Education in which digital technologies are systematically integrated into teaching and learning processes, including online, hybrid, and technology-enhanced face-to-face instruction.
Embodiment	Embodied presence, where the activity and identity of the student or teacher are connected to a physical or technologically mediated 'bodily' representation (e.g. through a TPR).
Engagement	The cognitive, emotional, and behavioural involvement of students in educational activities, demonstrated through active participation, motivation, interaction, and persistence.
Environmental awareness	Awareness of the physical and social learning environment, including the location of participants, ongoing activities, and contextual information relevant to learning and interaction.
Equity	The principle of providing fair access, participation, and learning opportunities by recognising and addressing differences in students' needs, circumstances, and barriers to participation.
Ethical and Cybersecurity Considerations (E)	The ethical principles, privacy practices, data protection measures, and participation norms that ensure safe and responsible TPR use.
Feeling presence	The subjective experience of being present in the learning environment, regardless of physical location.
Homebound	A student who cannot physically attend educational activities because of health-related circumstances and participates in learning remotely.
Hybrid learning	A form of learning in which students participate through a combination of face-to-face and remote learning modalities, supported by digital technologies.
In-class student	A student who is physically present in the classroom or other learning environment during instructional activities.
Inclusive Access and Engagement (I)	The design of learning conditions that promote equitable participation, social presence, belonging, and active engagement for all students.

Instructional Methods (I)	The instructional strategies, guidance, preparation, training, and support practices that enable effective participation in TPR-mediated learning.
Pedagogical Model	A theoretical framework that explains how learning occurs and guides the organisation of teaching and learning processes through educational principles, participant roles, and interaction patterns.
Pedagogical Design	The intentional and systematic planning of learning environments, activities, interactions, and support mechanisms to facilitate meaningful learning and participation.
Pedagogical Design Model	A structured framework that operationalises pedagogical principles by providing practical guidance for the design and implementation of teaching and learning activities within a specific educational context.
Pedagogical Integration (P)	The purposeful alignment of TPR uses with learning objectives, educational scenarios, learning activities, and assessment practices.
PEPCII Pedagogical Design Model	A pedagogical design model for integrating TPRs into synchronous hybrid learning environments.
Physical presence	The state of being physically located in the same environment as other participants, enabling direct face-to-face interaction, shared spatial awareness, and access to the immediate learning context.
Physical, Operational, and Educational Environment (P)	The physical, technical, and organisational conditions that support effective TPR-mediated participation in learning activities.
Remote participant	Any individual who takes part in a learning activity from a distance (e.g. students, teachers, or experts), typically through technologies such as TPRs.
Remote student	A student who participates in synchronous learning activities from a location outside the physical classroom and engages in communication, interaction, and learning through telepresence technologies, such as TPRs.
Representation	The mediated manifestation of a student, teacher, or other participant through a technological system (e.g. a TPR or avatar), enabling their visibility, communication, and participation within a physical learning environment.
Social presence	The participants' ability to perceive each other as 'real' and socially present in a technologically mediated environment.
Student- centred learning	Emphasis is placed on active participation, collaboration, problem-solving, and the student's individual needs.
Synchronous hybrid learning	A form of hybrid learning in which physically present and remotely participating students take part in the same lesson in real time.

Telepresence	Technologically mediated presence, where the user can perceive and influence a remote environment as if physically present there.
Telepresence-mediated learning	A learning process in which the student's participation, interaction, and presence are mediated through telepresence technology.
Telepresence Robot	A mobile robotic platform that enables a remote participant to move in a physical space, communicate, and be visible and audible to other participants.
Well-being	The psychological, social, and emotional well-being of a student or teacher in the learning environment, including the experience of safety, belonging, and balance.

Explanations of key terms and concepts used in the thesis.

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References

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Abstract

Integrating Telepresence Robots into the Teaching and Learning Process

This doctoral thesis addresses ensuring inclusive and meaningful participation of students in digital and synchronous hybrid learning environments. Despite the flexible learning opportunities created by educational technologies, remote students often experience social isolation, limited interaction, and a lower sense of social presence compared to those participating in face-to-face learning. The problem is particularly relevant in the context of hybrid learning, where ensuring equal learning opportunities remains challenging.

The aim of the doctoral thesis is to develop and validate a pedagogical design model for integrating telepresence robots (TPRs) into synchronous hybrid learning. The study focuses on how TPRs support remote students' social presence, active participation, and engagement, and improve the quality of the learning experience. The central research question of the study is: What is an effective pedagogical design model for implementing TPRs in the teaching and learning process?

A design-based research approach was applied in the study, which was conducted in three stages. In the first stage, a systematic literature analysis was carried out to map problems and needs. In the second stage, the PEPCII pedagogical design model was developed based on semi-structured interviews with instructors who had used TPRs, as well as reflections from students and teachers. In the third stage, the model was validated in authentic higher education learning situations, involving teachers and both remote and face-to-face students.

The results show that TPRs can improve remote students' sense of social presence, engagement, and active participation, provided that their use is supported by systematic pedagogical design. It also emerged that the effective implementation of technology requires clear pedagogical guidelines, institutional support, and consideration of social, ethical, and organisational aspects. The developed PEPCII model functions as a practical and empirically validated framework for the purposeful implementation of TPRs in hybrid learning.

The main contribution of the doctoral thesis lies in linking technological possibilities with pedagogical practice, offering a concrete design framework and implementation guidelines for higher education teachers. The study shows that the informed and pedagogically grounded use of telepresence technologies can increase the inclusiveness, interactivity, and quality of the learning experience in hybrid learning, while supporting more equal educational opportunities in the digital age.

Lühikokkuvõte

Kaugosalusrobotite juurutamine õppeprotsessi

Käesolev doktoritöö käsitleb õpilaste kaasava ja sisuka osaluse tagamist digitaalsetes ja sünkroonsetes hübriidõpikeskkondades. Hoolimata haridustehnoloogiate loodud paindlikest õppimisvõimalustest kogevad kaugõppijad sageli sotsiaalset isolatsiooni, piiratud suhtlust ning madalamat sotsiaalse kohalolu tunnet võrreldes kontaktõppes osalejatega. Probleem on eriti aktuaalne hübriidõppe kontekstis, kus võrdsete õppimisvõimaluste tagamine on jätkuvalt keeruline.

Doktoritöö eesmärk on välja töötada ja valideerida pedagoogiline disainimudel kaugosalusrobotite integreerimiseks sünkroonsesse hübriidõppesse. Uurimistöö keskendub sellele, kuidas kaugosalusrobotid toetavad kaugõppijate sotsiaalset kohalolu, aktiivset osalust ja kaasatust ning parandavad õpikogemuse kvaliteeti. Töö keskne uurimisküsimus on: milline on tõhus pedagoogiline disainimudel kaugosalusrobotite rakendamiseks õpi- ja õppeprotsessis?

Uuringus rakendati disainipõhise uurimistöö lähenemist, mis viidi läbi kolmes etapis. Esimeses etapis teostati süstemaatiline kirjanduse analüüs probleemide ja vajaduste kaardistamiseks. Teises etapis arendati PEPCII pedagoogiline disainimudel, tuginedes kaugosalusroboteid kasutanud õppejõudude poolstruktureeritud intervjuudele ning üliõpilaste ja õpetajate refleksioonidele. Kolmandas etapis valideeriti mudelit autentsetes kõrgkooli õpisituatsioonides, kaasates õpetajaid ning nii kaug- kui ka kontaktõppes osalevaid üliõpilasi.

Töö tulemused näitavad, et kaugosalusrobotid saavad parandada kaugõppijate sotsiaalse kohalolu tunnet, kaasatust ja aktiivset osalust, eeldusel et nende kasutamist toetab süsteemne pedagoogiline disain. Samuti ilmnes, et tehnoloogia tõhus rakendamine eeldab selgeid pedagoogilisi juhiseid, institutsionaalset tuge ning sotsiaalsete, eetiliste ja organisatsiooniliste aspektide arvestamist. Väljatöötatud PEPCII mudel toimib praktilise ja empiiriliselt valideeritud raamistikuna kaugosalusrobotite eesmärgipäraseks rakendamiseks hübriidõppes.

Doktoritöö peamine panus seisneb tehnoloogiliste võimaluste ja pedagoogilise praktika sidumises, pakkudes konkreetset disainiraamistikku ja rakendusjuhiseid kõrgkoolide õppejõududele. Uuring näitab, et kaugosalustehnoloogiate teadlik ja pedagoogiliselt põhjendatud kasutamine võib suurendada hübriidõppe kaasavust, interaktiivsust ja õppijate õpikogemuse kvaliteeti, toetades samal ajal võrdsemaid haridusvõimalusi digiajastul.

Appendix 1

Publication I

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Exploring the power of telepresence: enhancing education through telepresence robots

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Abstract

Purpose – This study aims to enhance the understanding of the current research landscape regarding the utilisation of telepresence robots (TPRs) in education.

Design/methodology/approach – The bibliometric and thematic analysis of research publications on TPRs was conducted using papers in the Scopus database up to 2023. The final analysis focused on 53 papers that adhered to the selection criteria. A qualitative analysis was performed on this set of papers.

Findings – The analysis found a rising trend in TPR publications, mostly from the USA as conference papers and journal articles. However, these publications lacked technology integration frameworks, acceptance models and specific learning design models. TPRs have proven effective in various learning environments, fostering accessible education, better communication, engagement and social presence. TPRs can bridge geographical gaps, facilitate knowledge sharing and promote collaboration. Obstacles to implementation include technical, physical, social and emotional challenges. Publications were grouped into four thematic categories: didactic methods of using TPRs, TPRs for educational inclusivity, TPR as a teacher mediator and challenges in using TPRs. Despite the significant potential of TPRs, their broader adoption in education is still facing challenges.

Research limitations/implications – This research solely analysed research papers in the Scopus database, limiting TPR publications with the keywords "telepresence robots", "learning", "teaching" and "education", excluding studies with different other keywords.

Originality/value – This study enhances understanding of TPR research in education, highlighting its pedagogical implications. It identifies a gap in the inclusion of technology integration frameworks, acceptance models and learning design models, indicating a need for further research and development.

Keywords Telepresence robots, Bibliometric analysis, Literature review, Education, Emerging technologies

Paper type Literature review

1. Introduction

Telepresence, coined by Minsky in 1980, refers to the utilisation of multimedia elements like sound, vision and touch to generate a feeling of physical presence in a distant location (Shen and Shirmohammadi, 2006). Although the idea of remotely operated robotic systems has been under study for several years, telepresence robots (TPRs) have gained significant attention in recent years. TPRs are movable devices equipped with cameras, microphones and interactive features, enabling users to control the robot's movements and engage in conversations using its audio-visual capabilities (Kristoffersson *et al.*, 2013). They have been used in medicine, elderly care, office work, museums, libraries, industry and education (Virkus *et al.*, 2023).

While not yet widely adopted, their rising popularity can be attributed to their potential for time and cost savings and their ability to improve communication and create a feeling of

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social presence. TPRs hold the potential to bridge geographical gaps, enabling individuals with chronic illnesses, disabilities, limited mobility or other constraints to actively engage in remote events by embodying themselves through a TPR. Consequently, this technology is unlocking novel prospects in remote work, communication, collaboration, education and is delivering substantial value across multiple sectors. However, their educational use has received little attention (Virkus *et al.*, 2023).

At the same time, TPRs have great potential in the context of synchronous hybrid learning. A comprehensive review conducted by Means *et al.* (2010) over a decade (1996–2008) reveals that blended or hybrid learning, which combines face-to-face and online components, has emerged as the most promising approach for education (Gleason and Greenhow, 2017). However, designing and implementing pedagogical strategies and technological systems that enable comparable learning experiences in synchronous hybrid learning poses challenges (Cain *et al.*, 2016). To successfully integrate TPRs into education, educators must carefully consider various aspects. These include defining the purpose and aligning learning goals, selecting appropriate pedagogical approaches, determining technical requirements, providing comprehensive training and support, ensuring accessibility and inclusion, prioritising privacy and security, addressing ethical considerations and implementing effective evaluation and feedback mechanisms. Considering these aspects ensures purposeful, pedagogically sound and goal-aligned integration of TPRs into education (Cain *et al.*, 2016; Charteris *et al.*, 2022; Gleason and Greenhow, 2017).

Numerous technology integration models and frameworks have been developed by educators and researchers to guide incorporation of technology into teaching and learning. For example, the Technological pedagogical content knowledge/TPACK framework (Koehler *et al.*, 2014), the substitution, augmentation, modification and redefinition model (Hamilton *et al.*, 2016), the level of technology implementation Framework (Moersch, 2010) and several others. These models and frameworks offer a structured approach to ensure that technology is purposefully and meaningfully incorporated, leading to improved educational experiences and outcomes. Typically, these frameworks and models outline key elements, stages or components that educators can follow to successfully integrate technology into their educational practices. These frameworks and models take into consideration various aspects, such as pedagogy, content, technology and learner needs.

To integrate TPRs into education, their acceptance plays a vital role. The adoption of new technology involves social and human factors, which are often examined through the lens of technology acceptance (Davis *et al.*, 1989). There are several well-known technology acceptance models (TAMs) that explain the factors influencing the acceptance and adoption of new technologies. For example, the TAM and its updated versions (Davis *et al.*, 1989), the unified theory of acceptance and use of technology (Venkatesh *et al.*, 2003) and the innovation diffusion theory (Rogers, 1995). Social cognitive theory by Albert Bandura (1986) has also been used to explain intentions to use technology (Ratten and Ratten, 2007). These models help educators understand and address user concerns while facilitating successful implementation of technology.

In addition, learning design models provide systematic frameworks for creating engaging, effective and impactful learning opportunities to help plan how to effectively integrate TPRs into teaching. However, there lacks a comprehensive overview on how educators use these frameworks and models while incorporating TPRs into education.

This study aimed to analyse educational applications of TPRs by examining relevant publications available in the Scopus database. The study was guided by the following research questions (*RQs*):

RQ1. What are the main tendencies in publication years, document types and lengths, publication authors and countries of origin?

RQ2. Which didactic methods have been used when integrating telepresence robots into the learning processes?

RQ3. What are the benefits and challenges of implementing telepresence robots in education?

The paper is organised as follows: Section 2 offers an overview of the related literature reviews. Section 3 outlines the research methodology. Section 4 presents the results of the study. Section 5 provides the discussion and Section 6 concludes the paper.

2. Related literature reviews

Several literature reviews have been conducted to investigate the role of TPRs in education. For example, Velinov (2021) identified 28 relevant studies on Google Scholar: 14 in primary education, nine in secondary education and 12 in higher education (HE). Some studies discussed TPRs across multiple educational levels. Notably, 12 studies highlighted the use of TPRs for conducting laboratory exercises and practical work. The studies identified positive features of TPRs, such as a sense of control over presence and interaction, a feeling of physical presence, intuitive use, effective real-time interaction, creating excitement and happiness and providing educational and social benefits and value. Negative features included audio challenges, visual obstacles, a lack of control over the TPR's movements and operations and connectivity issues. To enhance TPR functionality, suggestions encompassed improved adaptability, simplified stationary interface, discreet chat, resource sharing, user state indicators and remote student calls.

Charteris *et al.* (2022) analysed 17 papers from the University of New England library databases on the use of TPRs, both broadly and in schools, to foster virtual inclusion. The paper highlights issues such as portability, expenses, privacy, access protocols, access to materials, classroom positioning, student attendance and relationships, teacher education, engagement planning and power relations that need careful attention. The paper introduces an inclusivity model for TPRs to address these concerns, outlining physical, environmental, social, cultural, pedagogical and technological aspects. It provides a set of questions to guide practitioners in creating a supportive school environment for virtual inclusion.

Häfner *et al.* (2022) reviewed 70 papers on the use of TPRs in upper secondary and HE. The selection process for these papers is unclear, but the paper outlines eight educational scenarios identified from the literature:

- A remote educator teaches a class via a TPR (e.g. controlling the robot, interacting with students, maintaining eye contact and handling teaching materials).
- A remote expert advises students and teachers using a TPR (e.g. conducting a classroom observation, evaluating teaching quality, supporting students with disabilities and remote surgical teaching).
- A remote student participates in a class using a TPR.
- A remote student interacts with a local teacher using a TPR (e.g. language learning and authentic interactions with native speakers).
- A remote student collaborates with a local student using a TPR for joint problem-solving and discussions.
- A remote class communicates with a teacher located elsewhere using a TPR.

- A remote class interacts with an expert.
- Remote classes from different locations communicate and collaborate using TPRs.

The benefits of using TPRs were enhanced social presence, opportunities for remote teaching and learning from various locations and reducing travelling. Challenges included connectivity problems, limited interaction due to mechanical constraints and audio issues, difficulties in navigation and a narrow field of view.

Leoste *et al.* (2022a) examined the strengths and weaknesses of using TPRs in HE, identifying 13 relevant papers through Google Scholar. Three key themes emerged from the research:

(1) enhanced social presence;
(2) active classroom engagement; and
(3) a sense of physical presence.

Studies showed that TPRs enhance social connectedness satisfaction among users. Physical presence was important in TPR experience. The main concerns included technical issues, operator presence challenges and teaching-related problems, with connectivity issues being a recurring problem. Technical support demands, physical obstacles, sensory and communication issues, negative learning effects and increased teacher workload were also noted. Coordinating TPR settings was complex, and cognitive demands on operators were mentioned.

Chou *et al.* (2023) investigated factors influencing robot-assisted HE. They searched ten databases (e.g. PubMed, Excerpta Medica Database, Cumulative Index of Nursing and Allied Health Literature, IEEE Technology Xplore, Cochrane Library, Scopus, Web of Science, Education Resources Information Center, ProQuest and Psychological Information Database) and identified 28 studies. Barriers identified included issues such as unclear robotic audio and technical limitations related to both the software and hardware components of the robots. Facilitators included increased student engagement, improved distance learning experience and better knowledge acquisition. Their conclusion highlighted the promise of integrating robot-assisted education alongside traditional teaching methods. They suggested that future research should focus on specific robot types in similar educational contexts.

Fletcher *et al.* (2023) conducted a systematic literature review on the usage of TPRs in schools. They searched various databases, including PsychInfo, British Education Index, Web of Science, Education Resources Information Centre, Technology Research Database, Internurse and British Nursing Index. Among the 11 papers they identified, four themes emerged:

(1) potential of TPRs to promote inclusion;
(2) their ability to facilitate engagement;
(3) the influence of technical design; and
(4) user acceptability.

The paper highlighted predominantly positive views of TPRs, indicating their potential to enhance academic engagement, learning and reduce social isolation and loneliness. The obstacles were related to technical issues such as reliable Wi-Fi and the impact of misunderstandings and minimal sharing of information between users.

Virkus *et al.* (2023) analysed publications from the field of psychology and education in the Web of Science database from 1980 to 2022. They found limited interest in psychology and education compared to computer science. Among 24 papers, 12 were from education, mainly from the USA. The majority of papers underscored the positive impact of TPRs in promoting inclusivity and enhancing remote learning experiences, surpassing traditional videoconferencing in fostering social presence. TPRs were found to particularly benefit disabled individuals and language learners, while also expanding access to education in rural areas. However, their effective implementation necessitated meticulous design consideration due to challenges such as TPR availability, logistical complexities, technological requirements and the need for pedagogical support. Diverse research methods were used, including experiments, case studies, simulations, video analysis, surveys and interviews, involving participation from both students and teachers. Nevertheless, despite their potential, widespread acceptance of TPRs remained a significant challenge, underscoring the importance of robust pedagogical design and well-structured research endeavours.

In addition to papers focused solely on literature analysis, several articles incorporate brief literature reviews alongside empirical studies. For instance, Leoste *et al.* (2022a) provide an overview of TPR utilisation in education, highlighting advantages such as cost and time savings, remote accessibility for students with health-related challenges and enhanced inter-institutional connections. Additionally, TPRs contribute to the improvement of social presence, communication and relationships, and fostering global collaborations among educational institutions. While not yet mainstream despite some university trials, TPRs offer distinct benefits over traditional distance learning tools by bolstering engagement, persistence and empowerment. However, TPRs confront challenges related to connectivity, manipulation, navigation, social interaction and cost. Issues like limited camera field of view, audio/video transmission quality problems, privacy concerns and high-power consumption have also been reported. Furthermore, challenges include teacher resistance stemming from entrenched teaching practices.

Lei *et al.* (2022) underscored the utilisation of TPRs in education for the purpose of advancing equity and accessibility. TPRs play a crucial role in assisting ill and hospitalised students, facilitating a sense of normalcy and interaction with both instructors and peers. However, novice operators may encounter technical challenges in their use. TPRs serve as a means to connect students, enhance engagement, support distance and hybrid education, offer simulation capabilities, provide library support and have been applied for remote lectures, incorporating advanced features such as facial recognition and directional sound.

The range of publications scrutinised in literature reviews varied from 11 to 70, shedding light on the diverse applications of TPRs in education across all levels. Based on these literature reviews, TPRs offer a myriad of advantages, including cost savings through reduced travel expenses, augmented social presence, promotion of virtual inclusion, increased engagement, mitigation of social isolation, intuitive real-time interaction, control over presence and excitement factor. Furthermore, TPRs provide educational and social benefits, contributing to equity and accessibility by assisting ill students. However, they also face several challenges, including connectivity issues, limited camera field of view, audio/video quality problems, navigation limitations, interaction constraints, availability concerns, cost considerations, user acceptability challenges, privacy concerns and the need for logistical, technological and pedagogical support. Suggestions for enhancing TPR functionality encompass the incorporation of adaptable sitting/standing positions, simplified driving interfaces, discreet communication features, material sharing capabilities and noticeable indicators. These reviews underscore the potential benefits of TPRs while acknowledging the technical and implementation challenges, underscoring the importance of adopting inclusive and pedagogically sound approaches.

3. Methodology

To address the *RQs*, a systematic literature review was conducted following the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) methodology (Moher *et al.*, 2009). The PRISMA methodology is a well-established and widely accepted approach to conducting systematic reviews of the literature. It differs from other systematic review methods in that it provides a standardised and comprehensive checklist of items to be included when submitting a systematic review or meta-analysis, which helps to improve transparency and conduct high-quality, evidence-based reviews (Page *et al.*, 2021). Several authors argue that the use of the PRISMA methodology for conducting systematic reviews of the literature has several advantages over other methodologies due to its transparency, completeness, up-to-date guidelines, feasibility and reproducibility of research. PRISMA is widely accepted by journals and publishers as the standard for systematic reviews (Liberati, 2009; Bushe, 2011; Liu *et al.*, 2014; Brennan and Munn, 2021; Rethlefsen *et al.*, 2021; Sarkis-Onofre *et al.*, 2021; Trifu *et al.*, 2022). PRISMA has been updated and improved over time to ensure its relevance and applicability to current research (Page *et al.*, 2021).

The search was performed in the Scopus database, with a focus on the titles, abstracts and keywords of the articles. The subject terms used for the search comprised "telepresence robot*" AND "learning" OR "teaching" OR "education". Preliminary search resulted in 127 documents from which 53 were selected for the final research.

To identify highly relevant papers, criteria for inclusion and exclusion were meticulously crafted. The search was limited to studies published prior to 2 January 2023, comprising peer-reviewed journal articles, conference papers and book chapters in the English language that explored the utilisation of TPRs in education.

The paper selection process involved application of specific exclusion criteria. Prior to the screening phase, 21 documents were excluded; these documents were conference proceedings in favour of individual standalone papers. During the screening phase, eight papers were excluded due to a lack of full-text accessibility. In the eligibility phase, 45 papers were excluded for the following reasons:

- Papers that exclusively focused on the design of TPRs without addressing their use in education were excluded.
- General overviews lacking specific details or research findings.
- Papers describing workshops or demonstrations without substantial research or analysis of TPRs were excluded too.
- Papers that centred on social or holistic robots instead of TPRs in education were also excluded.

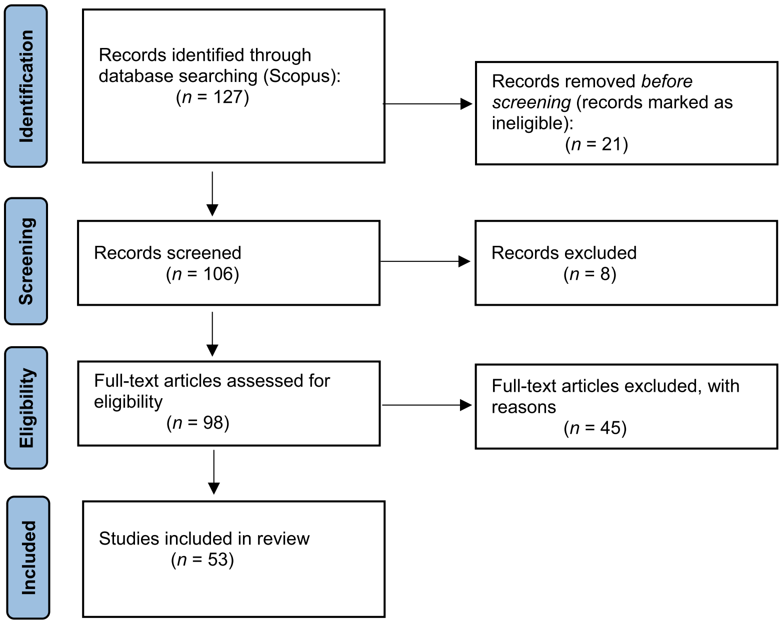
Figure 1 presents a step-by-step process of selecting research papers, following the PRISMA guidelines (Moher *et al.*, 2009). This selection process aimed to ensure the inclusion of relevant and high-quality papers for further analysis.

Firstly, a bibliometric analysis was conducted to answer *RQ1*, examining publication trends in terms of years, document types, lengths, authors and countries of origin. Then, an in-depth analysis of 53 publications was conducted in the second stage to address *RQ2* and *RQ3*. This in-depth analysis provided a deeper exploration of the use of TPRs in education.

4. Findings

4.1 Bibliometric analysis of paper

The first publication on TPRs in education in the Scopus database can be traced back to 2011. Since then, the number of TPR publications has grown, with the exception of 2019 and

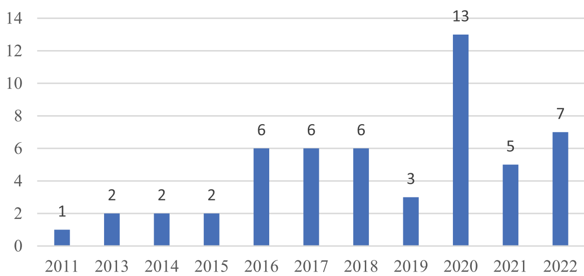


Source: Figure by authors

Figure 1. PRISMA flowchart

2021. Figure 2 illustrates the annual distribution of published papers starting from 2011. Notably, the year 2020 stands out as the most productive year, with a total of 13 publications. In 2022, there were seven publications, while in the years 2016, 2017 and 2018, six papers were published each year. The year 2021 saw five papers published, whereas 2019 witnessed three publications. For the years 2013, 2014 and 2015, there were two papers published annually, and in 2011, only one paper was published.

Figure 3 illustrates the distribution of publications across different types. Out of the total of 53 publications analysed, 27 were conference papers, accounting for 50.9% of the publications. On average, the conference papers had a length of 6.5 pages. Journal articles



Source: Figure by authors

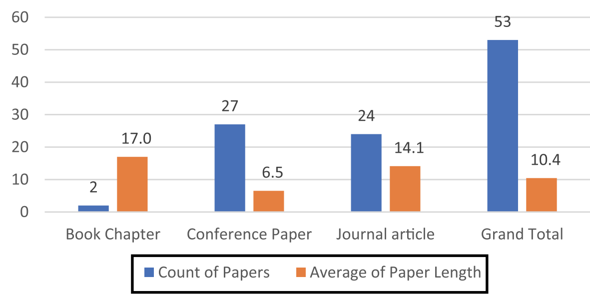
Figure 2. Number of publications per year

comprised 24 of the papers (45.3%), with an average length of 14.1 pages per article. Two of the papers fell into the category of book chapters, making up 3.8% of the total publications and had an average length of 17 pages.

A total of 149 authors contributed to the publications. Table 1 provides a list of authors who have contributed to more than two papers. Among them, Jian Liao and Veronica A. Newhart stood out as the most productive authors, having contributed to four papers each. Seven authors, namely, Elizabeth Cha, Jaclyn Dudek, Jeonghye Han, Maja J. Mataric, Fumihide Tanaka, Paul Tota and Mircea-F. Vaida, have each published three papers, and ten authors have published two papers.

Table 2 presents a list of countries that have made contributions to more than one paper. The majority of contributions originated from the USA, accounting for 25 papers (47.2%). European countries accounted for 13 papers (24.5%), with Romania contributing three papers (5.7%), the UK, Finland and France each contributing two papers (3.8%), Denmark, Estonia, Germany and Italy each contributing one paper (1.9%). Asian countries contributed seven papers (13.2%), with Japan having three papers (5.7%), Korea with two papers (3.8%) and Thailand and India each having one paper (1.9%). Australia contributed two papers (3.8%), while Mexico and Canada each had one paper (1.9%). Additionally, four papers (7.5%) were the result of collaboration between authors from different countries.

Out of the 53 papers analysed, 21 were about TPRs in HE (39.6%). Additionally, eight papers delved into TPRs within K-12 education, while seven specifically addressed TPRs within primary education. Three papers focused on TPRs in kindergarten and primary



Source: Figure by authors

Figure 3. Distribution of paper by type and average paper length by type

Authors	Count of papers
Jian Liao	4
Veronica A. Newhart	4
Elizabeth Cha	3
Jaclyn Dudek	3
Jeonghye Han	3
Maja J. Mataric	3
Fumihide Tanaka	3
Paul Tota	3
Mircea-F. Vaida	3

Source: Figure by authors

Table 1. List of authors who are published more than two papers

school settings, while two focused on secondary schools. Furthermore, two papers examined the role of TPRs in informal education settings. Notably, seven papers did not specify the educational level (Table 3).

Almost half of papers (26 out of 53 papers, 49.1%) do not reveal the specific discipline that was studied, or it cannot be named because the study was made over a longer period of time, during which students attended many different subjects. Eight papers (15.1%) were conducted in language learning classes. Five (9.4%) in medicine, three (5.7%) were conducted in engineering. TPR was used in information and communication technology, education and chemistry, all of which accounted for two (3.8%) each. Accounting and costs, physical education class, psychology and business communication classes each accounted for one (1.9%) study (Table 4).

The subsequent sections provide an overview of the utilisation of TPRs in education as discussed in the papers reflected in the Scopus database.

4.2 Telepresence robots in education

The papers analysed in this study can be classified into the following four categories:

(1) didactic methods of using TPRs;
(2) TPRs for educational inclusivity;
(3) TPR robot as a teacher mediator; and
(4) challenges in using TPRs.

Country	Count of no.	% of publications
USA	25	47.2
Japan	3	5.7
Romania	3	5.7
Australia	2	3.8
Finland	2	3.8
France	2	3.8
Korea	2	3.8
UK	2	3.8

Source: Figure by authors

Table 2. Distribution of publications between countries

Level of education	Count of publications	% of publications
HE	21	39.6
K-12	8	15.1
Not specified	7	13.2
Primary school	6	11.3
Kindergarten, primary school	3	5.7
Secondary school	2	3.8
Informal education	2	3.8
Kindergarten, primary and secondary school	1	1.9
All levels	1	1.9
Health care	1	1.9
Medical school	1	1.9

Source: Figure by authors

Table 3. Distribution of publications between educational levels

Table 4.
Distribution of publications between disciplines

Row labels	Count of title	% of publications
Not specified	26	49.1
Language learning	8	15.1
Medicine	5	9.4
Engineering	3	5.7
ICT	2	3.8
Education	2	3.8
Chemistry	2	3.8
Public administration	1	1.9
Accounting and costs	1	1.9
Physical education class	1	1.9
Psychology	1	1.9
Business communication	1	1.9

Source: Figure by authors

4.2.1 Didactic methods of using telepresence robots. The literature presents various didactic methods for using TPRs in education. These methods span across various educational context and offer unique advantages.

4.2.1.1 Enhancing practical skills and teamwork. TPRs offer good opportunities for developing practical and teamwork skills. However, proper preparation of simulations and the learning environment is crucial for effective outcomes (Molloy *et al.*, 2016; Mudd *et al.*, 2020; Shaw *et al.*, 2018; Wong *et al.*, 2021). TPRs have been shown to enhance medical education by bridging the gap between classrooms and hospital environments and developing practical and teamwork skills. They facilitate simulations for paediatric scenarios and clinical practice, offering real-life experience for students (Molloy *et al.*, 2016; Mudd *et al.*, 2020; Shaw *et al.*, 2018). Furthermore, TPRs also prove effective in patients' care and clinical assessment, serving as an alternative or complementary method (Mudd *et al.*, 2020). In addition to their educational benefits, TPRs promote interprofessional collaboration, as demonstrated by Wong *et al.* (2021) with pharmacy and nursing students working together as a team. In addition to medical education, students can gain practical experience by using TPRs to explore various locations and events beyond the confines of the classroom. For instance, in the research methods class for postgraduate students, there were demonstrations using TPRs, highlighting the advantages of attending academic conferences (Lueg *et al.*, 2020).

4.2.1.2 Remote laboratory work. TPRs serve as avatars for remote lab work, allowing students to conduct experiments as if they were physically present. This approach enables instant feedback and mobility within the lab settings (Denojean-Mairet *et al.*, 2014; Maxwell *et al.*, 2017). Challenges, such as adjusting voice volume and visual cues, underscore the need for perceptual negotiation and consensus in creating tangible learning spaces with TPRs (Furnon, 2018). Maxwell *et al.* (2017) introduced a module that included a mobile remote shake table laboratory, providing students with the opportunity to remotely participate and conduct physical shake table experiments in real-time using smart mobile devices. This extended lab used various options and demonstrated that TPRs are valuable tools for obtaining instant feedback on experiments by allowing for movement around the lab.

4.2.1.3 Workshops and hands-on learning. TPRs offer great opportunities to enhance workshops and collaborative learning experiences. By using TPRs in workshops, educators can expand their reach, increase accessibility and provide dynamic and interactive learning experiences that are not limited by physical location. This technology opens up new possibilities for innovative and inclusive workshop formats. Several papers demonstrate how workshops incorporating short lectures and practical skills training have been developed using TPRs, targeting both teachers (Okundaye *et al.*, 2020) and students (Leoste *et al.*, 2022b). TPRs have enabled remote participation, making hands-on sessions accessible to a wider audience.

4.2.1.4 Foreign language teaching. TPRs have been shown to have great potential in promoting foreign language learning through authentic communication practice, enabling interactions between native English speakers and English learners in remote settings (Liao *et al.*, 2022; Liao and Dudek, 2017; Liao and Lu, 2018). Authors such as Liao and Dudek (2017), Liao and Lu (2018) and Liao and Dudek (2020) have explored TPRs' potential in providing immersive language learning experiences. These studies reveal that TPRs can simulate authentic environments and facilitate interactions with native speakers in real-time. Furthermore, TPRs have been shown to enhance cultural awareness and language proficiency (Liao *et al.*, 2022). They also offer visual access to learning materials and increase social presence compared to static videoconferencing tools (Jakonen and Jauni, 2021). Liao *et al.* (2022) proposed three design principles for foreign language teaching: situated learning, scaffolded learning processes and enhanced learner agency. In their study, Yun *et al.* (2013) proposed a new form of teaching robot system for English classes that uses a TPR controlled by a teacher from a remote site.

4.2.1.5 Virtual field trips. TPRs offer an innovative and immersive way to conduct virtual field trips, enhancing the educational experience by providing students with the opportunity to explore distant locations in real-time. Chen *et al.* (2022) compared teachers using TPRs for virtual field trips to those watching pre-recorded videos. The TPR group showed higher scores in embodiment, social presence and engagement, indicating a preference for TPRs in virtual field trips.

4.2.1.6 Integrating segregated educational environments. TPRs offer solutions for integrating segregated educational environments by bridging physical divides and facilitating inclusive learning experiences. Sheehy and Green (2011) studied how children from a mainstream primary school and a special school interacted visually and verbally using TPRs. Although the technology was not reliable for everyday use, it showed potential for facilitating interaction among physically segregated children within educational environments.

4.2.1.7 Storytelling and vocabulary command. TPRs can be creatively integrated into storytelling and vocabulary command activities to make learning more engaging and interactive for students. In kindergarten and primary school settings, TPR exercises have been found to improve student response rates and vocabulary command during language learning activities. Tanaka *et al.* (2014) demonstrated that TPR-based storytelling language games yield higher student engagement and language acquisition compared to traditional methods.

4.2.1.8 Synchronous hybrid learning. TPRs can play a valuable role in enhancing synchronous hybrid learning, which combines both in-person and remote instruction. They bridge the physical gap between remote students and the classroom, facilitating more inclusive and interactive learning experiences. Capello *et al.* (2022) investigated student and faculty experiences with TPRs in a synchronous hybrid learning environment. The study revealed that while both in-person and distance learners expressed high satisfaction and social connectedness, technology issues occasionally disrupted student learning. Additionally, faculty members lacked TPR knowledge and pedagogical strategies for the hybrid environment. The study suggested designating a student as a technology navigator to address setup and troubleshooting issues, although this role may divert their attention from learning.

Comparing student attendance preferences, TPRs were found to enhance presence, self-awareness and expression compared to other distance learning technologies. Shin and Han (2016) found that Korean elementary school students preferred using TPRs to communicate with their distant classmates over other teleconferencing technologies. This improved student engagement and inclusivity. Interestingly, according to Fitter *et al.* (2020), teachers preferred in-person students, while students themselves preferred attending via videoconference.

In sum, TPRs have found diverse applications across various educational contexts. They have expanded the horizons of education, transcending the boundaries of traditional classrooms. TPRs enhance medical education through simulations, enable immersive remote laboratory work, facilitate hands-on learning in workshops, enable virtual field trips, integrate segregated educational environments, support postgraduate research methods classes and improve engagement in foreign language teaching. Additionally, TPRs enhance language learning in kindergarten and primary school, and they have the potential to enhance synchronous hybrid learning environments. To maximise the benefits of TPRs in education, professional development and support are essential for effective pedagogical integration in hybrid learning settings. TPRs can overcome barriers such as social and geographical limitations, enabling diverse students to interact and explore different classrooms. These findings highlight the valuable contribution of TPRs in improving educational experiences and removing learning obstacles.

4.2.2 Telepresence robots for educational inclusivity. Several publications have explored the diverse ways in which TPRs contribute to enhancing educational opportunities and inclusivity. These studies reveal the potential benefits TPRs offer in educational settings:

- supporting homebound students;
- facilitating the reintegration of students who have experienced long-term absences due to chronic illnesses or cancer;
- enabling access for students with health problems; and
- engaging older adults in educational activities.

4.2.2.1 Supporting homebound students. One significant application of TPR technology is in supporting homebound students, enabling them to actively engage in the learning process. Ahumada-Newhart and Olson (2019) suggested implementing TPRs for homebound students, emphasising the importance of attending lessons, participating in learning activities, communicating with classmates and teachers, navigating the school environment, completing assignments and taking tests. The primary focus is to ensure the active involvement of homebound students in the classroom (Weibel *et al.*, 2020).

4.2.2.2 Facilitating reintegration. TPRs play a crucial role in facilitating the reintegration of students who have experienced long-term absences due to chronic illnesses or cancer. Studies conducted by Schmucker *et al.* (2020) and Weibel *et al.* (2020) highlight how TPRs address the sense of social disconnection experienced by these students. Additionally, adjusting the TPR camera settings, such as using a still image, can accommodate health-related concerns while maintaining the student's individuality and personal presence (Schmucker *et al.*, 2020).

4.2.2.3 Enabling access for students with health problems. TPRs are valuable tools for enabling active students' involvement in the classroom during temporary or short-term absences. De Jong (2021) demonstrates that TPR usage benefits graduate students by supporting their retention and programme completion, enhancing time efficiency, maintaining a work-life balance and creating a sense of physical and social presence in the classroom. Thompson and Chaivisit (2019) indicate that the utilisation of TPRs provides injured students with an opportunity to actively participate in the learning process, fostering a sense of social presence and eliminating the isolation often associated with standard videoconferencing systems. Poyet's (2018) research demonstrates how TPRs help students with disabilities, pursuing remote master's degrees, focus on listening, leading to improved comprehension and recall of lecture materials. Jadhav *et al.* (2018) highlighted how TPRs enable children with disabilities to actively engage in the classroom, overcoming physical limitations and fostering a more inclusive learning environment.

4.2.2.4 Engaging older adults in educational activities. Beyond traditional student populations, TPRs offer a unique avenue for involving older adults in educational activities after their retirement. Okamura and Tanaka (2016) demonstrated how TPRs facilitate active engagement and contribution from older generations, such as teaching the art of Japanese paper folding craft Origami at the primary school level.

In sum, these publications collectively illustrate the potential of TPRs to address various challenges and enhance educational experiences. They empower homebound students and those with health issues, support reintegration and provide inclusivity. TPRs improve the accessibility of education for remote learners and offer new opportunities for older adults to engage in teaching. By operating TPRs remotely, students can actively participate in class discussions, collaborate with peers and stay connected to the learning environment even when unable to attend in person.

4.2.3 Telepresence robot as a teacher mediator. TPRs have gained significant attention as mediators between instructors and students. This section discusses several notable studies that explore the role of TPRs as a teacher mediator.

4.2.3.1 Enhancing English language learning. Several studies have shown the potential of using TPRs in language learning (Liao *et al.*, 2022; Liao and Dudek, 2017; Liao and Lu, 2018). In a study conducted by Yun *et al.* (2013), Korean primary school students learned English over a three-month period with the native teacher meditated with a TPR. A field pilot study demonstrated that the tele-operated robot system led to improvements in standardised tests, indicating its potential effectiveness in enhancing educational systems, particularly in English education.

4.2.3.2 Addressing teacher shortages. The shortage of teachers, a prevalent issue in many regions, has found a potential remedy with the help of TPRs. A study by Puarungroj and Boonsirisumpun (2020) showed that TPRs can effectively solve the shortage of teachers. Their study developed a TPR for remote teaching in Thailand, addressing teacher shortages and external support needs. The results from a classroom setting where artificial intelligence was taught through TPR-mediated instructor highlighted high student satisfaction with communication and interaction with the TPR, with a willingness to continue studying with this innovative approach in future classes (Puarungroj and Boonsirisumpun, 2020).

4.2.3.3 The height factor in telepresence robots. In interpersonal interactions, taller stature often provides an advantage in conveying a sense of dominance or authority to others. However, shorter robotic platforms are favoured for robotic telepresence. This preference is based on considerations of work stability, user convenience and psychological comfort (Cole, 2014; Stulp *et al.*, 2015). The impact of a TPR's height on an instructor's ability to manage students in robot-assisted learning is explored in the study conducted by Bae and Han (2017). They investigated whether the height of a TPR had an impact on an instructor's ability to control a large number of students in robot-assisted learning. The experiment showed that the height of the TPR does not significantly affect instructor authority, but students perceive shorter robots as friendlier.

4.2.3.4 Telepresence robot-mediated vs physically present instructor. In a controlled laboratory study, Okundaye *et al.* (2020) revealed substantial disparities in students' experiences and outcomes when using TPRs for hands-on technology learning as opposed to traditional in-person instruction. The research underscored the promising role of TPRs in facilitating remote hands-on learning but also underscored the importance of addressing various design considerations. These considerations encompass aspects such as physical representation, spatial awareness, maintaining multimodal coherence and enhancing control mechanisms within the TPRs.

4.2.3.5 Telepresence robot-mediated instructors vs autonomous social robots. In their pioneering study, Edwards *et al.* (2016) explored how college students perceive robots in educational roles. The study compared students' perceptions of a human instructor using a TPR and an autonomous social robot delivering the same lesson. Remarkably, students found both instructors, human and robot, to be credible. However, they awarded higher credibility ratings to the robot acting as the teacher, which had a discernible impact on their learning outcomes. Despite both instructional agents delivering the lesson in a controlled manner, students reported experiencing more affective learning when the robot assumed the role of the teacher, as opposed to the robot acting as the instructor. This difference in perception led to distinct effects on behavioural learning outcomes. The study unveiled a noteworthy direct effect: a potential machine heuristic emerged, suggesting that students were more inclined to follow behavioural guidance provided by the autonomous social robot. However, the study also acknowledged the need for further exploration in this area, indicating that future research should delve deeper into understanding the nuanced dynamics of human–robot interactions in educational contexts.

4.2.3.6 Telepresence robots vs holographic projection. Holographic telepresence, in which holographic displays project three-dimensional images of remote participants, creates the illusion of being physically present in the same space. This technology provides a more realistic representation of individuals and enhances the telepresence experience (Ramirez-Lopez *et al.*, 2021). Luévano *et al.* (2015) compared the use of a TPR and holographic projection in college classes, finding that students perceived the combined use of these telepresence devices as the most efficient, allowing them to experience the presence of the professor through a human-scale holographic image, bi-directional audio and video and autonomous movements of the remotely controlled robot.

In conclusion, these studies collectively underscore the versatility and potential of TPRs as valuable tools in the educational landscape. From language learning enhancements to addressing teacher shortages and reshaping instructional dynamics, TPRs offer innovative solutions that hold promise for the future of education. The height of the TPR does not impact instructor authority significantly. TPRs combined with holographic projection create a better sense of presence. Students find robots posing as teachers more credible, leading to different learning outcomes and a preference for affective learning. However, the successful integration of TPRs requires careful consideration of design, context and pedagogical strategies to maximise their benefits and create meaningful learning experiences for students.

4.2.4 Challenges in using telepresence robots. The utilisation of TPRs in education presents a promising avenue for enhancing the learning experience. However, numerous studies consistently highlight recurring challenges and essential requirements for their effective implementation in education.

4.2.4.1 Connectivity challenges. A prevalent issue that hampers the functionality of TPRs is the unreliable Wi-Fi connection (Leoste *et al.*, 2022b). TPRs rely on a stable and high-speed internet connection to establish real-time communication between the remote operator and the robot. Any interruptions or fluctuations in Wi-Fi connectivity can result in lag, delays or even disconnections, making it challenging for the operator to control the robot effectively. Poor connectivity can lead to pixelated or frozen video, as well as distorted or interrupted audio, impacting the operator's ability to see and hear what is happening in the remote environment. To address this, Tota and Vaida (2020a) propose a solution that uses light fidelity (Li-Fi) technology based on visible light communication.

4.2.4.2 Manoeuvrability and space constraints. Another common problem is manoeuvring the TPR within the room. Manoeuvrability and space constraints have a significant impact on the functionality of TPRs and their ability to perform effectively in different environments. TPRs need to move around physical spaces, whether it's a classroom or a lab, or another location. Manoeuvrability is crucial for avoiding obstacles, reaching desired locations and interacting with objects or people. Space constraints, such as narrow doorways, cluttered areas or tight corners, can hinder the TPR's ability to navigate effectively. In extreme cases, it may become stuck or unable to access certain areas. Tota and Vaida (2020b) propose obstacle-avoiding TPRs, whereas Leoste *et al.* (2022b) recommend arranging the physical space to facilitate TPR movement.

4.2.4.3 Audio and video challenges. Audio and video challenges of TPRs directly impact the quality of communication and perception in remote environments. Cha *et al.* (2017) gathered insights from TPR designers and researchers to understand the functionality of a TPR operated by a remote student. Challenges include maintaining high-quality audio and video amid environmental noise, which hampers engagement, communication and visual perception. Recommended design solutions include a wider range microphones and cameras, strategic TPR positioning, directional microphones or noise filtering, continuous views of the teacher's area and additional cameras for collaboration and material sharing. Rueben *et al.* (2020) suggested integrating an audio-level feedback system into the TPR user interface.

4.2.4.4 Physical and behavioural challenges. Physical and behavioural challenges encompass difficulties and limitations associated with the physical attributes and behaviours of the TPRs themselves, which affect their interaction with users and the environment. Cha *et al.* (2017) identified challenges with embodiment and interaction aspects of TPRs in classrooms, such as positioning, limited gaze cues, restricted head movement, distracting motion and mechanical appearance. Interface challenges in TPR control are also addressed, emphasising the need for simpler, student-oriented interfaces. Teachers expressed concerns about lacking control over TPR operation for safety and classroom management. Participants suggested using a chat interface for private communication with the teacher and displaying text during audio or control issues. This would allow feedback, warnings, muting student volume or disabling TPR movement to maintain classroom control. Zhang *et al.* (2018) developed an educational TPR capable of autonomous navigation, targeted student engagement, audio detection, speech recognition, face-to-face interaction, generating maps and teacher control using face detection. The system also facilitated leveraging classroom devices for teaching support, enhancing instructor credibility and improving the usability of educational platforms.

Cha *et al.* (2017) emphasised the importance of including the TPR's operator both from educational and social perspectives. However, designers often faced challenges in participating actively in group activities, as most interactions were limited to students conversing among themselves. Adding robot arms as a solution was proposed but deemed costly, complex and requiring more bandwidth. Instead, a more feasible approach is to provide physical materials to remote students, enabling their participation in the same activity at home.

4.2.4.5 User experience enhancement and training needs. Several publications emphasise the importance of preparing students, teachers and parents for the effective use of TPRs in education. Newhart and Olson (2017) stress the need for training on technology capabilities and creating a safe learning environment. Guidelines in students' handbooks, such as maintaining a stable internet connection and muting when not speaking, can support smooth TPR usage (Rinfret, 2020). Powell *et al.* (2021) suggest that informative resources and websites should provide explanations and stories from teachers about effective TPR engagement in the classroom. Schools can incorporate integration guidelines into their policy manuals to streamline TPR use (Rinfret, 2020). Additionally, conducting Zoom meetings to demonstrate TPR functionalities and allowing students to try them out is a valuable suggestion (Gamberini *et al.*, 2022). Stakeholders focus group interviews also highlighted the need for strategies and guidelines for implementing TPRs in schools (Perifanou *et al.*, 2022). Cha *et al.* (2017) also emphasised the importance of proper training and one-to-one interaction to promote inclusion and help the classroom adjust their behaviour to accommodate the remote student and the TPR's presence. The HANCON model can help stakeholders understand the potential applications of TPRs in education. It examines decision-making factors for TPR adoption and evaluates acceptability post-implementation (Han and Conti, 2020). To enhance the overall user experience of TPRs, it is beneficial to use an interactive game environment for practice before their actual deployment (Cha *et al.*, 2017).

4.2.4.6 Ethical and privacy considerations. Ethical and privacy issues for TPRs are important as they interact with humans in a variety of settings. Key concerns include ensuring privacy through cameras and microphones, data security, data retention and sharing policies, operator behaviour, especially when controlling TPRs remotely, considerations related to children and vulnerable populations, ethics of autonomous operation, defining the boundaries of remote presence, cultural sensitivity, fraud prevention and potential dual use. Organisations using TPRs should provide operator training, prioritise data security and engage in open dialogue to ensure ethical TPR use while respecting individuals' rights and dignity. Sharkey (2016) discussed ethical concerns and potential privacy issues associated with teaching through TPRs.

4.2.4.7 Challenges related to specific target groups. Tanaka *et al.* (2013) expressed concern that the use of child-operated TPRs has not yet been thoroughly examined. The study focuses on the development of a tricycle-style operation interface, designed based on classroom field observations to be intuitive and usable even for young children without extensive instructions. Comparing the tricycle-style interface to a standard video-game controller, the former demonstrated superior operational performance.

Schmucker *et al.* (2020) identified essential factors for the successful implementation of TPRs derived from a project that supported the daily school routine of seriously ill pupils and facilitated contact with friends, regardless of whether they attended class from home or from the hospital. The factors included: sick student's interest and acceptance, hospital and school's interest and acceptance, internet connection availability at school, hospital and home, presence of a contact person at home and school, avatar/hardware quality, classmates' interest and acceptance, microphone and camera quality, avatar weight/portability, selectable screen output (livestream or photo display), availability of emoticons for communication and LEDs/instructions for retreat and signalling. Addressing these factors is crucial for successfully implementing TPRs and integrating seriously ill pupils into the school environment, regardless of their location.

4.2.4.8 Challenges for planning the use of telepresence robots in the classroom. Integrating TPRs in the classroom entails careful planning and consideration. This includes determining the optimal placement of TPRs, organising effective pair/group work, establishing movement guidelines and identifying necessary TPR involvement. The teacher should provide verbal or non-verbal cues to ensure active student participation in the learning process (Jakonen and Jauni, 2022). To effectively use TPRs in learning, Cha *et al.* (2017) stress the importance of considering students' cognitive and social development, as well as their familiarity with technology.

In sum, studies identified recurring challenges in the implementation of TPRs. These challenges include connectivity issues, manoeuvring the TPR within the room, maintaining high-quality audio and video, addressing embodiment and interaction issues, interface design considerations, promoting inclusion, privacy and personalisation. Proposed solutions include using Li-Fi technology, obstacle-avoiding TPRs, physical materials for remote students, simpler interfaces and chat interfaces for communication. Additionally, the potential value of TPRs in childhood education and factors for successful implementation have been discussed. The successful implementation of TPRs in the classroom relies heavily on the involvement of stakeholders, including parents, school administrators and teachers.

4.3 Research methods used in the studies

The use of TPRs in education has been studied using various methods. Interviews were the most frequently used method, with a frequency of 22, accounting for 41.5% of all methods used. Experiments were the second most frequently used method, with a frequency of 16 (30.2%). Surveys/questionnaires were used 12 times (22.6%), case-studies were used seven times (13.2%) and an observation and real-field test were each used six times (11.3% each). Scenarios, prototyping and videorecording were used five times each, each representing 9.4% of the methods. Other methods like mixed-methods, qualitative analysis and focus group interviews were used three times each, accounting for 5.7% each. Methods like quantitative analysis, literature review, model development, written reflections and a pilot study were used less frequently, each accounting for less than 2% of the total methods used. Table 5 provides an overview of the diversity of research methods used in the studies and the frequency of their use.

Several studies used multiple methods simultaneously, with only three studies reporting that they used a mixed-methods design. There were no clear patterns regarding the relationship between the disciplines and methods used. In the field of medicine, scenario-based simulations were used in four out of five research papers, and in language teaching, experimental methods were used in four studies.

5 Discussion

5.1 Bibliometric analysis of telepresence robot publications

The analysis reveals a growth in the number of TPR-related publications in the education field, starting from 2011. This growth is significant, with the exception of 2019 and 2021. The peak year was 2020, which saw 13 publications, indicating a surge in interest and research activity related to TPRs in education. Conference papers are the most common (51%), although they tend to be shorter, averaging around 6.5 pages. Journal articles make up a substantial portion (45%) as well, with an average length of 14.1 pages per article. Book chapters contribute to a smaller percentage of the total publications but have a longer average length of around 17 pages. This suggests that some researchers chose to contribute their work to book chapters, offering comprehensive perspectives on specific aspects of TPRs.

A total of 149 authors contributed to the publications, with some authors contributing to multiple papers, which may imply that certain individuals or research groups are actively involved in studying TPRs. Jian Liao and Veronica A. Newhart are the most productive

Methods	Frequency of using the method	Frequency of occurrence %
Interviews	22	41.5
Experiments	16	30.2
Survey/questionnaire	12	22.6
Case-study	7	13.2
Observation	6	11.3
Real-field test	6	11.3
Scenarios	5	9.4
Prototyping	5	9.4
Videorecording	5	9.4
Mixed-methods	3	5.7
Qualitative analysis	3	5.7
Focus group interviews	3	5.7
Quantitative analysis	2	3.8
Literature review	1	1.9
Model development	1	1.9
Written reflections	1	1.9
Pilot study	1	1.9

Source: Figure by authors

Table 5.
Research methods used in the studies

authors, each having contributed to four papers. Several other authors have also made substantial contributions, with three papers each. This information can be valuable for identifying key researchers in the field.

The majority of contributions (47.2%) originated from the USA. This finding indicates a strong research presence in the USA and suggests that the country has been at the forefront of TPR research. European countries collectively contribute a significant portion (13), with Romania, the UK, Finland and France being notable contributors. Asian countries had seven, Australia two, Mexico and Canada each had one paper, indicating a global interest in TPRs in education. Moreover, four papers resulted from collaborations between authors from different countries, highlighting the international cooperation in studying TPRs.

HE is the most frequently studied (39.6%). K-12 education, primary education and kindergarten also receive attention. The existence of papers that do not specify the educational level or address multiple levels indicates a diverse range of research interests in TPRs across various educational contexts. TPRs have been used in various fields, but language learning, medicine and engineering are some of the prominent disciplines where TPRs have been applied. This diversity reflects the adaptability of TPRs across different subject areas in education.

This bibliometric analysis provides an overview of the growth, contributors and focus areas of TPR-related research in education. It offers useful information for researchers, educators and policymakers interested in understanding the landscape of TPRs in educational contexts, facilitating further research and collaboration.

5.2 Didactic methods in integrating telepresence robots into the learning process

Analysed publications showcased the diverse applications of TPRs in various educational activities. TPRs have been effectively used in lectures, workshops, remote lab work, discussions, team/pair work, storytelling games for language learning, simulations, virtual field trips, integrating segregated educational environments and for synchronous hybrid learning. In addition, the combined use of TPRs and holographic projection was seen as efficient in creating a sense of presence. This wide range of applications demonstrates the versatility of TPRs as instructional tools in different contexts and subject areas.

Several papers provide specific examples of how TPRs have been beneficial in certain educational domains. For example, in medical education, TPRs have been found to enhance practical skills and teamwork during simulations. They can serve as avatars for remote lab work, enabling students to actively participate in experiments and receive instant feedback.

In foreign language teaching, TPRs offer advantages in terms of remote participation and access to authentic communicative environments. They enhance social presence and engagement for remote learners compared to static videoconferencing. TPRs can virtually immerse learners in outdoor environments and provide real-time interaction with native speakers. Design principles for telepresence-place-based foreign language learning, including situated learning, scaffolded learning processes and enhanced learner agency, are also suggested. These examples highlight the potential of TPRs to facilitate language learning and create immersive and engaging language learning experiences. TPRs have also positive effects on language learning in kindergarten and primary school settings. This suggests that TPRs can be valuable tools for early childhood education, contributing to language development and engagement among young learners.

The impact of using TPRs in the learning process on the achievement of learning outcomes remains largely unexplored. Only one study conducted by Liao *et al.* (2022) has delved into this question and found a positive influence on learning outcomes when TPRs were incorporated. Specifically, the research revealed that telepresented students exhibited improvements in both listening and speaking skills, indicating the potential benefits of integrating TPRs into educational practices. This indicates a research gap in understanding the full extent of the effects of TPR utilisation on different aspects of learning. Further research is needed to comprehensively investigate and evaluate the impact of TPRs on various learning outcomes, such as knowledge acquisition, critical thinking, problem-solving and overall academic performance.

Furthermore, the analysed papers lacked the inclusion of certain frameworks or models, such as technology integration frameworks or models, TAMs and specific learning design models. Similarly, some papers failed to provide a description of the didactic methods used in classes where TPRs were implemented as part of the learning process. This indicates that these aspects were not explored or reported in the publications or are not used in the application of TPRs teaching. This information gap indicates that there may be a need for more detailed investigation of the pedagogical approaches used in TPR implementation.

Despite these gaps, however, the examples provided in the analysed literature shed light on the potential of TPRs as versatile and impactful tools for enhancing teaching and learning experiences in different domains. The findings of this study shed light for the first time on didactic methods of using TPRs that have not been previously analysed in the literature.

5.3 Benefits of using telepresence robots in education

The adoption of TPRs in educational contexts offers a wide range of advantages, ranging from heightened accessibility and improved communication to increased engagement and enhanced social presence. Additionally, TPRs possess the capacity to bridge geographical gaps, facilitate participation for individuals facing constraints, address teacher shortages, provide time and cost savings and expand the horizons of learning opportunities. Leoste *et al.* (2022a) and Virkus *et al.* (2023) also emphasised the benefits of enhanced social presence and time and cost savings. Charteris *et al.* (2022) and Fletcher *et al.* (2023)

underscored the importance of promoting virtual inclusion and increasing engagement in their respective literature reviews.

One of the paramount benefits of TPR in education is their ability to break down traditional barriers, rendering education more accessible to a broader spectrum of students. TPRs allow individuals facing challenges like chronic illnesses, limited mobility, disabilities or other constraints, enabling them to actively participate in remote learning experiences by embodying TPR. This inclusivity not only dismantles the confines of the physical classroom but also encourages the exploration of diverse learning environments to accommodate students with varying needs. These challenges align with the study conducted by Lei et *al.* (2022).

The effectiveness of TPRs has been demonstrated in various educational contexts. They have proven to be invaluable for enhancing cultural awareness, facilitating intercultural communication and promoting proficiency in foreign languages. By providing access to authentic communication settings, TPRs empower remote learners to engage in real-time conversations with native speakers. Additionally, TPRs have found their niche in medical education simulations, remote laboratory experiments, postgraduate research methods classes and virtual field trips. The integration of didactic methods with TPRs allows educational institutions to deliver high-quality education to remote or underserved regions, thereby extending their reach and fostering inclusivity.

Furthermore, TPRs serve as conduits for experts and professionals from diverse locations to remotely share their knowledge and experiences. Through the integration of didactic methods, these experts can deliver specialised training, conduct workshops or deliver guest lectures, enriching the educational experience for students. This fosters collaboration and the exchange of ideas across geographical boundaries, empowering students to benefit from a diverse range of perspectives. The synergy between didactic methods and TPRs holds immense potential for enhancing the overall educational landscape. By harnessing the power of TPRs, educational institutions can aspire to create more inclusive, engaging and dynamic learning environments that cater to the needs of an increasingly diverse student population.

5.4 Challenges of implementing telepresence robots in education

The challenges discussed in the analysed papers can be divided into technical, physical, social and emotional challenges encountered during the use of TPR.

Technical challenges include unreliable Wi-Fi connections, difficulties in maintaining high-quality audio and video amidst environmental noise and problems with adjusting voice volume and visual cues. Velinov (2021) and Häfner *et al.* (2022) also emphasised connectivity issues and Velinov (2021) and Chou *et al.* (2023) noted audio/video quality problems. Additionally, limitations arise from the inability of TPR-mediated students to physically interact with learning materials in the classroom. The papers suggest several areas for improvement, such as avatar weight/portability, selectable screen output, communication tools like chat and emoticons and instructions for retreat and signalling. These challenges are indeed significant and can disrupt the learning process. Ensuring the reliability and maintenance of TPRs is crucial to avoid interruptions in the implementation of didactic methods. Furthermore, the reliability of TPRs is crucial for their effectiveness, and continuous improvement in this regard is essential. However, it is important to note that technology is constantly evolving, and many of these issues can be mitigated with better hardware and software solutions.

Physical challenges involve positioning and mobility of TPRs, restricted gaze cues and head movement, distracting motion and a mechanical appearance, which can hinder their effectiveness. These challenges are also mentioned in previous literature reviews (Velinov, 2021; Häfner *et al.*, 2022; Leoste *et al.*, 2022a, 2022b). While these challenges are real, they are inherent to the nature of TPR technology and may require innovative design solutions to overcome.

Social and emotional challenges, such as concerns about control over TPR operation, privacy and personalisation, were also identified as significant issues. Teachers expressed worries about safety and classroom management when using TPRs. These concerns are valid, as they touch on ethical and psychological aspects of TPR use. It is essential to address these concerns to gain the trust of all stakeholders, including students, teachers and parents. Privacy concerns were also mentioned by Charteris *et al.* (2022), Leoste *et al.* (2022a) and Fletcher *et al.* (2023) and social and emotional challenges by Virkus *et al.* (2023).

The papers highlight the importance of adequately preparing students, teachers and parents for TPR use through training and guidelines. This is a critical aspect of successful TPR integration. Without proper training and guidelines, the potential benefits of TPRs may not be fully realised and technical challenges may become more pronounced.

Several recommendations were provided, such as incorporating guidelines in student handbooks, creating informative resources and integrating TPR usage guidelines into school policy manuals. These recommendations are practical and can contribute to the smoother integration of TPRs into the educational environment. They offer a structured approach to addressing the challenges mentioned earlier.

Involving all stakeholders, including teachers, students and parents, in the decision-making process is highlighted as a valuable practice. This inclusive approach ensures that the perspectives and needs of the educational community are considered. It can lead to more informed decisions and better outcomes when implementing TPRs.

5.5. Research methods used in the studies

One noteworthy aspect that should be mentioned is the diversity of research methods used in TPR-related educational studies. This diversity reflects the complexity of the field and the effort to gain a comprehensive understanding of TPRs. It is a positive sign that researchers are open to using various methodologies to investigate the effectiveness and implications of TPRs in education.

Interviews are the most frequently used method (41.5%) of all methods used. While interviews can provide valuable insights into the experiences and perspectives of teachers, students and practitioners, it is essential to consider their limitations. Interviews are subject to biases, such as social desirability bias or interviewer bias, which can affect the validity of the findings. Researchers should be aware of these limitations and use them judiciously in their studies.

Experiments are the second most frequently used method (30.2%) that demonstrate the commitment of researchers to establishing causal relationships and testing the effectiveness of TPRs. However, it is crucial to note that educational experiments can be challenging to conduct due to ethical and practical considerations. The studies often do not delve into the specifics of these experiments, leaving questions about their design and the validity of their results.

Only three studies reported using a mixed-methods design, indicating a relatively low adoption of this comprehensive approach. Combining qualitative and quantitative methods can provide a more nuanced understanding of TPRs in education. Researchers might benefit from using mixed methods more frequently to triangulate findings and strengthen the validity of their research.

Quantitative analysis, literature review and model development were used less frequently, each accounting for less than 2% of the total methods used. This underrepresentation of quantitative methods is noteworthy because they can offer valuable statistical insights into the effectiveness and generalisability of using TPRs. A more balanced approach that incorporates both qualitative and quantitative methods could enhance the overall quality of research in this area.

In sum, the diversity of research methods used in TPR-related educational studies is a positive indication of this area of research. However, a critical examination of these methods should also consider their limitations and the need for a more balanced use of qualitative and quantitative approaches. Additionally, context and research rigour are crucial factors to consider when evaluating the overall quality of research in this field.

6 Conclusion

This study provides an investigation of the role of TPRs in the field of education, encompassing a range of aspects, including bibliometric analysis, didactic methods, benefits and challenges. Starting with the bibliometric analysis, it is evident that TPR-related publications in education have experienced growth since 2011, reaching a peak in 2020. This surge in interest is reflected in the variety of publications, with conference papers being the most prevalent, followed by journal articles and book chapters. Furthermore, contributions have come from authors worldwide, with the USA leading the way, highlighting the global significance of TPRs in education.

TPRs have demonstrated their adaptability by finding applications across diverse educational levels and fields. When examining didactic methods, it becomes apparent that TPRs have been deployed in a wide array of educational activities, ranging from traditional lectures to innovative virtual field trips and synchronous hybrid learning. These examples underscore the versatility of TPRs as instructional tools. Noteworthy benefits of TPRs have been observed in fields such as medical education, foreign language teaching and early childhood education. However, there is a research gap regarding the impact of TPRs on learning outcomes, emphasising the need for further investigation. Some publications also lack detailed descriptions of the pedagogical approaches used in TPR implementation.

Adoption of TPRs has introduced numerous advantages. These encompass heightened accessibility, improved communication, increased engagement and the ability to overcome geographical barriers. Additionally, TPRs have emerged as a means to include individuals facing various constraints, enabling them to actively participate in remote learning experiences. Their effectiveness extends to cultural awareness, intercultural communication, foreign language proficiency and various educational contexts.

Nevertheless, challenges in implementing TPRs in education persist. These challenges encompass technical issues such as Wi-Fi connectivity problems, audio-video quality concerns and limitations in interaction capabilities. Physical challenges involve restrictions in TPR mobility and their mechanical appearance. Social and emotional challenges include privacy apprehensions and teacher concerns regarding classroom management. To address these challenges, adequate preparation through training and the establishment of guidelines is paramount. Recommendations put forth include the integration of guidelines, the development of informative resources and active involvement of stakeholders in decision-making processes.

The use of various research methods, often in combination, highlighted the diverse approaches to studying TPRs in education. The diverse array of research methods used in these studies reflects the complex nature of TPR research, underscoring the importance of taking a holistic approach to comprehend their impact on education fully.

In sum, TPRs have emerged as versatile tools in the educational landscape, offering a multitude of benefits while presenting technical, physical, social and emotional challenges. While the potential of TPRs is evident, it is crucial to address these challenges and conduct further research to understand their impact on learning outcomes fully. Additionally, involving all stakeholders and sharing best practices are essential steps towards the effective and informed integration of TPRs into educational settings. This holistic approach can ensure that TPRs contribute positively to the evolving landscape of education. In addition, the authors of this study emphasise the necessity for the development of didactic models based on educational theories that can provide effective support to teachers, enabling them to seamlessly integrate TPRs into the teaching and learning process.

The trends in the growth of TPR publications in education described in the paper have several implications for future research:

- The significant increase in TPR-related publications since 2011, with a peak in 2020, suggests a growing interest in the field. Future studies could look more closely at the reasons for this increased interest. What specific events or technological advances may have triggered this increase in TPR-related research? Identifying the drivers could provide valuable insights into the direction of future research.
- The analysis highlights the prevalence of conference papers, journal articles and book chapters. Future research could explore the differences in depth and quality of research between these publication types. Are conference papers more exploratory and do journal articles provide more in-depth analysis? How do book chapters contribute to a comprehensive perspective? Analysing these aspects can provide guidance to researchers on the most effective publication channels for disseminating TPR-related results.
- Identifying key authors is crucial for understanding the landscape of TPR research. Future studies can focus on their contributions and expertise. In addition, international collaboration in TPR research is noteworthy. Investigating the impact of such collaboration on the quality and diversity of research could be promising for future studies.
- The dominance of the USA in TPR research is a noteworthy revelation. It is worth investigating whether specific policies, sources of funding or institutions have propelled TPR research in the USA. Additionally, the participation of other countries from Europe, Asia and beyond signifies that TPRs are a worldwide cause for concern in education. To comprehend the utilisation and research of TPRs across various regions, comparative studies can be carried out.
- The wide range of educational levels and subject areas in which TPRs have been implemented requires further investigation. Future research should delve into the effectiveness of TPRs in various educational contexts and levels. Furthermore, an examination of the integration of TPRs across different disciplines, such as language learning, medicine and engineering, can provide valuable insights into the adaptability and impact of TPRs in varied educational domains.
- The bibliometric analysis presents an overview of the current research on TPRs in education while revealing potential areas of investigation.

Future research should focus on identifying regions or educational levels with limited TPR-based research. Such identification can help to guide future research efforts and address any gaps in the literature. The aforementioned trends presented in the paper establish a groundwork for subsequent scholarly exploration on TPRs in education.

Researchers can use this information to shape their studies, identify research gaps and explore emerging trends in this field, contributing to the advancement of educational outcomes through TPRs.

This study has several limitations. Firstly, it solely focused on analysing research papers within the Scopus database, thereby encompassing a restricted number of scientific publications pertaining to TPRs. Moreover, the analysis was limited to publications specifically labelled with the term "telepresence robots" in the Scopus database. Consequently, this paper fails to discuss several pertinent studies that either fall outside the scope of the Scopus database or use alternative keywords.

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Further reading

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Appendix 2

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Enhancing synchronous hybrid learning with telepresence robots: a PEPCII pedagogical design model for remote and onsite student engagement

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Introduction: The aim of this article is to provide a report on the development of a pedagogical design model for the effective adoption of telepresence robots (TPRs) in synchronous hybrid learning settings.

Methods: Following the design thinking approach, we conducted three qualitative studies. In the first study, we examined the needs of and opportunities for using TPRs in education as well as some of the related challenges. This was based on the personal experiences of six academic staff members in two Estonian higher education institutions. Building on the first study, we designed a 13-week synchronous hybrid undergraduate-level course using TPRs. The course was delivered to six students. Based on the students' homework and written feedback, the first prototype of a pedagogical design model was subsequently developed. In the third study, this model was piloted with 56 teachers by means of a two-hour hands-on synchronous hybrid workshop.

Results: Based on the teachers' feedback, the prototype was further improved and the PEPCII Pedagogical Design Model was completed. The PEPCII model comprises six central components that address key barriers to the adoption of TPR-s in education: Physical Operational and Educational Environment, Ethical and Cybersecurity Considerations, Cognitive and Physical Limitations, Pedagogical Integration, Inclusive Access and Engagement, and Instructional Methods.

Discussion: The PEPCII model addresses critical barriers to TPR adoption in education. Future research is required to validate the model in varied classroom settings over longer durations, and to assess impacts on engagement and well-being of TPR users, on-site students, and instructors.

KEYWORDS

telepresence robot, pedagogical design model, synchronous hybrid learning, social presence, technology acceptance

1 Introduction

Emerging technologies offer many new opportunities for education. At the same time, adopting them in education constitutes a complex social process that, in order to succeed, should keep pace with rapid and often unpredictable technological advances. While allowing for equipping students with advanced skills demanded on the labor market, designing technology-supported pedagogies and developing the necessary classroom practices require a thorough grasp of the educational processes. Ensuring the effective adoption of new technologies also requires careful consideration of the stages of learning and environmental factors (Leoste et al., 2021). Haphazard adoption of new technologies may easily have an effect quite different from the one expected.

Emerging technologies have been found having a positive effect on the effectiveness of hybrid learning, particularly with regard to improving the quality of synchronous hybrid learning. Synchronous hybrid learning means teaching face-to-face and remote students simultaneously in real time (Raes et al., 2020). According to Fabian et al. (2024), the main challenges of synchronous hybrid learning include students feeling excluded and disconnected from their peers and experiencing difficulties in collaborating with other students. The perceived lack of social engagement may lead to the loss of attention to learning, having a negative impact on learning outcomes. The central question remains how to ensure the well-being and effective participation of everybody present in the synchronous hybrid learning environment.

Telepresence robots (TPRs) constitute a novel remote learning technology potentially suitable for use in synchronous hybrid learning environments. The concept of telepresence was first introduced by Minsky (1980). A TPR can be described as a teleconferencing system on wheels, providing remotely located participants with a physical presence in the classroom (Tsui et al., 2011). Compared to traditional videoconferencing, TPRs offer higher levels of social presence, allowing remote participants to move around, freely choosing their position in the room, and dynamically changing their interaction partners (Cha et al., 2017). Social presence is defined as "*the degree to which a person is perceived as a 'real person' in mediated communication*" (Short et al., 1976). Such features make TPRs a promising tool for giving students access to education in times of emergencies or when access is hindered by health-related or other issues (Weibel et al., 2020; Page et al., 2021). Despite these benefits, the adoption of TPRs in education faces several challenges. While some studies, such as Elmimouni et al. (2024), offer recommendations for enhancing the TPR-mediated learning experience, most of the available research focuses primarily on the problems associated with their technical use. For instance, Perifanou et al. (2022), Velinov et al. (2021), and Häfner et al. (2023) have discussed various technical limitations of and challenges related to using TPRs in educational settings.

Kasuk and Virkus (2024) have suggested that to avoid focusing merely on technical issues and to allow for shifting the attention to creating learning designs for classroom practices, TPR implementation studies should rely on technology integration frameworks and pedagogical design models. Various such frameworks and models have been developed for the purposes of assessing the perceived usefulness of technology in education and the ease of its integration. Applicable for real life situations, these models can guide the adoption of new technologies in education as well as in other organizational settings. Among the literature reviewed by Kasuk and Virkus (2024), covering the period from 2011 to 2022, only a few studies (Fischer et al., 2019; Han and Conti, 2020) had used technology acceptance models. These models included the Technology Acceptance Model (TAM) by Davis (1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) by Venkatesh et al. (2003). Besides the studies focusing on TAMs available in the Scopus database, the articles published between 2022 and 2024 on the use of TPRs in education included the following: (a) Mascret et al. (2023) used pre- and post-tests as research instruments to assess how older adults adopt guidance via TPR, relying on TAM constructs such as perceived usefulness, perceived ease of use, perceived enjoyment, and the intention to use; (b) Huun and Slaven (2024) assessed the perceived usefulness and ease of use of technology by students in simulations, building their study on the respective TAM constructs; finally, (c) Arthanat et al. (2023) developed a set of UTAUT-based guiding questions to explore the possibilities of using TPRs in training older adults in the context of creating telehealth opportunities.

In addition to using UTAUT and TAM, several available studies have been guided by the principles of the Technological Pedagogical Content Knowledge (TPACK) model. TPACK (Mishra and Koehler, 2006) is a framework that helps teachers integrate technology into their pedagogies by combining content knowledge (understanding the subject matter), pedagogical knowledge (knowing how to teach effectively), and technological knowledge (understanding how to use technology in the classroom). The TPACK framework is particularly significant as the developers tend to design technological solutions according to their personal preferences, while overlooking the pedagogical aspects (McGraw Hill Canada, 2019). The TPACK framework explains how technology can support teaching, allowing for presenting content in new ways. Using the TPACK model can improve educational outcomes, as it ensures that technology is integrated purposefully and in alignment with pedagogical best practices, and appropriate for subject-specific content. Teachers with strong experience in using TPACK are likely to create more engaging, personalized, and future-ready learning environments that meet diverse student needs and prepare them for a technology-driven world (Inan and Lowther, 2010).

In addition to the previously mentioned models, other available models are specifically designed for adopting TPRs in education. TRinE (Telepresence Robots in Education) 4D is a four-category model by Perifanou (2023), describing a pedagogical approach for adopting TPRs in the classroom while using action research methodology as its basis. TRinE 4D includes the following pedagogical factors in adopting TPRs: (a) the educational context, (b) the educational TR settings, and (c) the teaching methods and tools. The model consists of the following stages: *define* (analyze information regarding the subject and students), *describe* (describe the number of participants involved via TPR, the role of TPR-mediated participants, and the types of TPR), *decide* (select teaching methods and tools), and *design* (plan the process). The model has been designed to support teachers, instructional designers, and other users in adopting TPRs in education (Perifanou, 2023). Chan et al. (2022) have developed a 4C model to adapt TPRs into HyFlex classrooms. The 4C model includes the following components: *content* (teaching materials), *collaboration* (active learning through collaboration), *community* (presence and sense of belonging), and *communication* (interaction with the teacher and other students).

Both the 4C and the TRinE 4D models start from the micro level while adopting TPRs. Perifanou (2023) and Chan et al. (2022) emphasize while developing their models that the adaptation of TPRs must consider the subject matter and its specifics, the students and their needs, as well as cover the selection of teaching methods that enable the collaboration and TPR-mediated participation, focusing on content. In the case of both models it remains, however, unclear which technology acceptance or adoption model, framework, or theory they rely on. Neither of the models addresses ethics and cybersecurity concerns or considers environmental setup issues in their use of TPRs. While there is limited research available that addresses either technology acceptance or pedagogical approaches in the context of TPRs, there is also a notable absence of comprehensive pedagogical design models that would encompass both approaches specifically for the purposes of TPRs.

To fill this gap, the research project described in the current article has aimed to develop such a model for the purposes of a more effective integration of TPRs into synchronous hybrid learning environments. The article is organized in the following manner: the second section outlines the research methodology and describes the empirical studies, the third section presents the overall results, the fourth section offers the PEPCII model, the fifth discusses the findings, and the sixth and final section concludes the study.

2 Empirical studies

The research project presented here was conducted from October 2023 to July 2024 and included three empirical studies (see Figure 1) to explore systematically the adoption of TPRs in higher education.

The first study included interviews with six higher education teaching staff members from Estonia to explore teachers' experiences and identify challenges and opportunities in the adoption of TPRs. Based on the results of this study, we have developed learning designs supporting the use of TPRs in student learning. As the next step, the second study piloted the learning designs in a 13-week synchronous hybrid course, with all students attending in telepresence mode. In the third and final study, which relied on the results from the previous studies, we tested the pedagogical design model prototype by piloting it during hands-on workshops for teachers. Double 3 (Double Robotics), Ohmni (Ohmni Labs) TPRs, and the TEMI v3 (Robo TEMI) robot assistant with the TPR functionality were used in all three studies. In some cases, the participants already had previous experience using these particular types of robots.

The Design Thinking Process (Brown, 2008) served as the guiding framework structuring the research. While the first study provided input for understanding teachers' needs, challenges, and opportunities in using TPRs in the learning process, the second study offered an opportunity to test the initial concept of the pedagogical design model. Testing the learning designs created from the initial pedagogical design model in the second study further included students' expectations, challenges, and opportunities regarding TPR use in learning. In the second study, we piloted the learning designs and developed the first pedagogical design model as a result of testing. During the third study, feedback was gathered for the purposes of the prototype development, ultimately leading to creating the PEPCII model. Each study was guided by a relevant research question. Based on the answers to these questions, we propose our comprehensive pedagogical design model for integrating TPRs in synchronous hybrid learning environments.

The validity of the research results is ensured by means of using a design thinking-based iterative process and three empirical studies (see Figure 2). We had three connected studies that helped develop the pedagogical design model. The data collected from the interviews with the teachers, the students' reflections and the focus group interviews combined with the workshops have allowed us to use data triangulation to strengthen the internal validity of the results. To ensure constructional value, we applied thematic coding in data analysis. While prototyping the pedagogical design model, testing and revising it strengthened the reliability of the research.

To guide our study, we formed the research questions, leaning on the iterative design thinking-based research process, grounding each next question in the empirical evidence from the previous stage. The first research question (RQ1) was a result of the need to find out practical barriers that were identified during preliminary teacher interviews, and of the gaps in existing literature about technology integration in hybrid settings – viewed from the perspective of technical and pedagogical challenges that teachers encounter with TPRs. Our goal was to ensure that the next research stages were based on real-life experience and practical realities. The second research question (RQ2) was based on the knowledge from Study 1 and had a theoretical emphasis on two core challenges that are frequently brought out in synchronous hybrid learning research: social presence

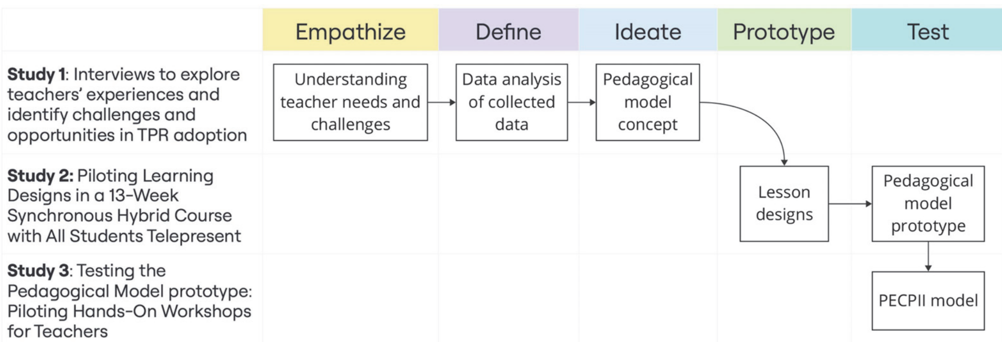

FIGURE 1
The Study design describes activities in all three studies that align with the Design Thinking process: empathize, define, ideate, prototype and test.

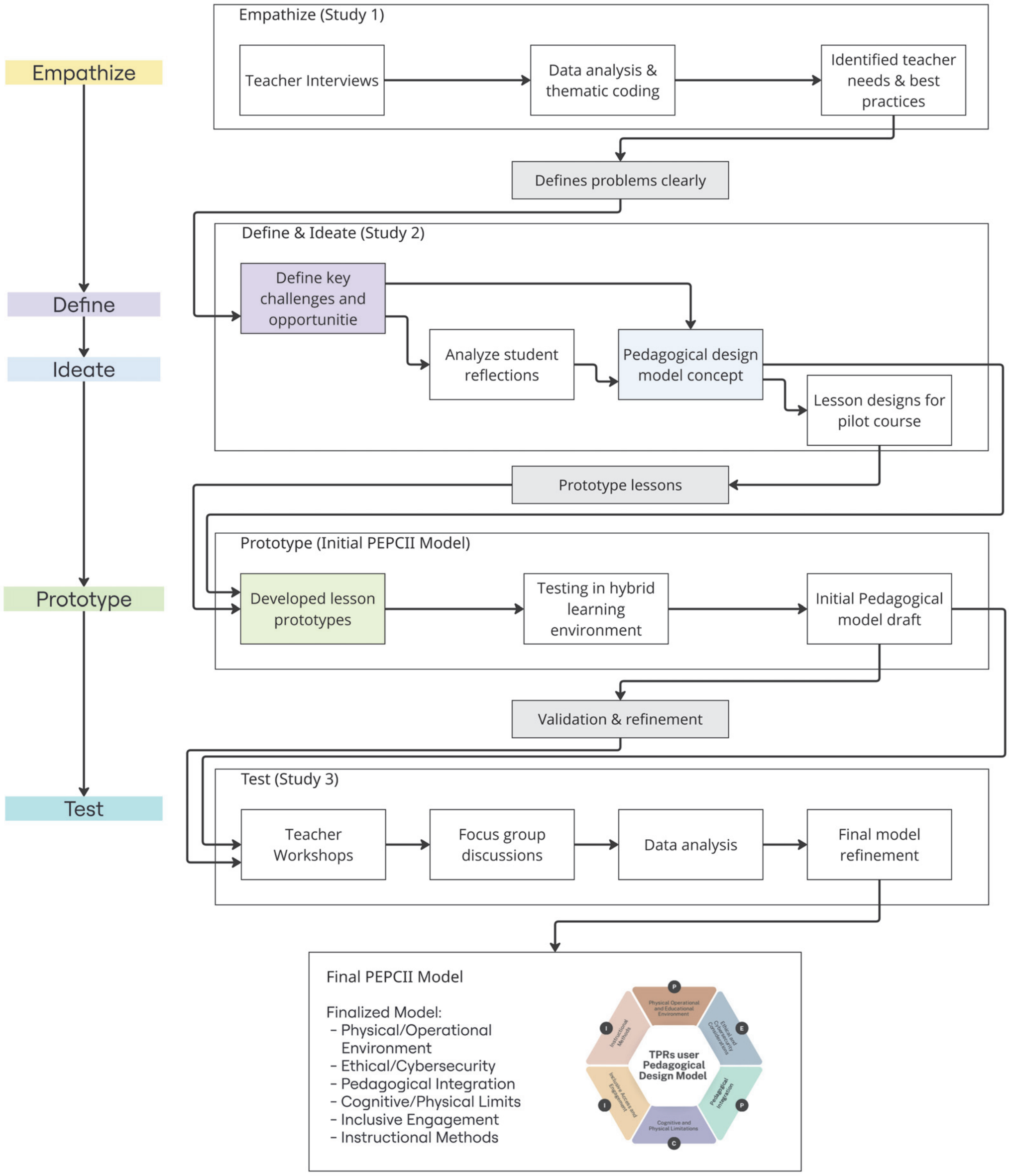

FIGURE 2
Flowchart of the PEPCII Pedagogical Design Model development.

and student engagement. We focused on the factors that influence students' perceived presence and engagement with TPRs. Thus, RQ2 addressed the need to understand student experiences deeply, and aimed to ensure that besides technical and teaching-related aspects, the pedagogical model considered also student-centric elements necessary for effective learning. The third research question (RQ3) used the findings from Studies 1 and 2 to provide broader validation and refinement for the emerging pedagogical model. The focus was on identifying specific educational scenarios suitable for productive TPR use and factors enhancing or limiting their effectiveness. By explicitly targeting conditions and factors critical for successful TPR integration, this research question intended to bridge theory and practice, ultimately contributing actionable and empirically validated recommendations for educators and institutions.

2.1 Study 1: interviews to explore teachers' experiences and identify challenges and opportunities in TPR adoption

The research question for Study 1 is the following:

> *RQ1*: What technical and pedagogical challenges do teachers encounter while using TPRs in teaching, and what impact do these challenges have on the quality of teaching and student engagement?

2.1.1 Methods and materials

The study included teachers from Estonian higher education institutions with prior experience in conducting or having attended TPR-mediated lessons. At the time of the study, teachers with sufficient experience of using TPRs were found in only two higher education institutions. All teachers meeting these criteria were invited to participate in a semi-structured interview. A total of six teachers, aged 30 to 67, participated in the interview. Four interviews were conducted in Estonian and two in English. The group included two female and four male participants. Given that TPR constitutes an emerging technology that remains underutilized in education, a purposive sample of experts was selected, with their shared opinions grounded in their practical experience with the adoption of the new technology.

The interviews conducted via Zoom and Microsoft Teams between October and November 2023 were recorded with the participants' consent. The transcriptions were prepared using Tekstiks.ee (Olev and Alumäe, 2022) and Notta.ai, followed by manual error correction. Thematic content analysis (Smith, 1992) revealed the key categories related to the teachers' technical solutions, classroom limitations, the importance of external support (e.g., assistants), and practical recommendations for novice TPR users. Figure 3 illustrates the concept map of the interviews' thematic content analysis.

2.1.2 Results: the challenges and opportunities in TPR adoption

The interviews allowed for identifying three main cases of TPR use in education: (1) *conducting lessons mediated by a TPR by remote teachers*, including the active presentation of learning content, such as slides, drawings, and diagrams; (2) *enabling students to participate remotely* in classroom activities and discussions when they are unable to attend in person; (3) *facilitating teachers' remote participation in events,* training, seminars, or meetings through TPRs.

The teachers who participated in our research emphasized several *technical prerequisites* for the effective use of TPRs. Most often they highlighted the issues such as clear audibility and visibility as critical factors influencing the quality of communication, particularly in the context of teaching in large classrooms. They also suggested using multiple screens or a single large screen, preferably with 4K resolution, to allow for the simultaneous use of the TPR interface and other necessary tools for presenting the learning content. It was suggested that adding an extra communication channel, such as a video conferencing solution, would improve the visibility of teaching content to the entire class. The teachers stressed that to improve the quality of sound, the voice of a remotely present teacher should be transmitted through a separate audio channel.

One teacher described the importance of the TPR's location in the classroom in the following manner: "*I solved the problem by positioning myself right next to the large interactive whiteboard with the robot and drawing on it as if I were physically present. I used Zoom's Whiteboard to draw with the mouse.*" (I1) To ensure clear communication as one of the pre-requisites for the inclusion of all students, particularly in noisy or acoustically poor classrooms, the teachers considered it critical to choose a *quiet environment* for the TPR use, as well as using high-quality headphone and microphone

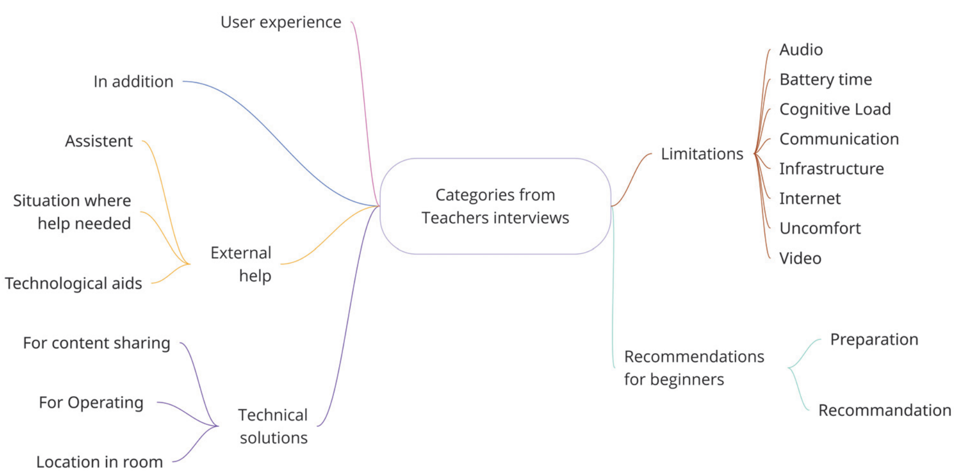

FIGURE 3
Conceptual map of Study 1 Thematical Categories. This mind map organizes key themes extracted from interviews with teachers, highlighting areas such as user experience, technical solutions, external help, limitations (e.g., audio, cognitive load, infrastructure), and recommendations for beginners.

sets. While some teachers felt that built-in laptop speakers and microphones were sufficient for audio transmission at the basic level, they noted that in more demanding environments better quality equipment might be needed.

The interviews revealed several *limitations* to teaching caused by the use of TPRs. Noting that facial expressions play an important role in supporting non-verbal communication, the teachers identified their *limited ability to use body language* as one of the significant challenges. The *low quality of the voice transmission* was often mentioned as an issue to be considered while choosing a suitable audio equipment. One participant commented on the quality of signal transmission within the TPR's communication system: "*Sometimes I was not getting good quality sound and picture. Because of this, I had to change my position in the classroom quickly to get a better view and a better audio and video quality.*" (I6) Additionally, the teachers stressed that *relying on the internet* and the poor quality of connection often led to delays, making the use of the TPR difficult. *The lack of a text-based communication channel* was also mentioned as a distinct challenge, making it difficult to share teaching resources in real time and as a result of this – hindering teaching. Another limitation mentioned was *the speed of the TPRs' movement*, as the robots' inadequate speed may easily complicate conducting discussions and cause delays in teachers' responses, particularly in more dynamic classroom situations.

One of the often-mentioned issues in the interviews was the *availability of designated support staff* or teaching assistants who would support the smooth delivery of TPR-mediated teaching. The presence of the support staff would allow the teacher to focus solely on delivering a lesson while the assistant would deal with all technical issues. During the lesson, the assistant might also provide feedback to the teacher regarding any particular technical issues and concerns, such as the quality and volume of the audio signal. Together with teaching assistants, teachers can remotely plan the integration of TPRs in their teaching, adapting the learning environment to accommodate TPRs' movement, and test the equipment for planned TPR supported activities. More experienced assistants could also provide additional on-site support, for example presenting teaching materials.

Our interviewees offered recommendations to new TPR users. The participants stressed the significance of thorough *preparation*. It was suggested that teachers should consider how to use TPRs in engaging students in discussions. One interviewee argued for a thorough preparation in the following manner: "*You must prepare thoroughly to avoid your teaching being disrupted. Using a robot should not disturb other students.*" (I2) Before conducting a lesson using a TPR, the equipment should be checked regarding the internet coverage in the classroom, the robot's battery life, and the quality of audio and video transmission. Another interviewee described the required pre-lesson activities: "*One limitation is the battery life of the robot. I always check it in the storage room one or two hours before the class*." (I5) Attention should also be given to the teacher's appearance on the TPR screen. One important recommendation to teachers was to attend introductory lessons provided by experienced TPR users. This would allow teachers to better prepare for their classes, choosing effective communication strategies as well as strategies to compensate for their inability to use body language while communicating with students.

The interviewees suggested conducting *pilot trials* before offering full-scale TPR-mediated lessons to further refine teachers' TPR using skills. This would allow new TPR users to develop their skills in facilitating group discussions and other classrooms activities while receiving immediate feedback from experienced TPR users. They should also learn how to identify video blind spots and audio signal distortions. New robot users should also be made aware of the ethical and cybersecurity concerns entailed in TPR-facilitated teaching. One interviewee pointed out the merits of small-scale piloting: "*You need to see the robot in action – how it moves in the classroom, what it does, and how it sounds.*" (I3).

Some of the participants also stressed the importance of *ongoing professional development* to help TPR users build their confidence. Creating peer groups where new techniques might be shared, challenges discussed, and new methods and equipment presented was one of the ways to support teachers using TPRs in professional development. Continuing professional development allows for appreciating technology supported education as a living and evolving practice, as opposed to mechanical incorporation of various gadgets in classroom activities.

The insights gained from *Study 1* formed the foundation for the design of the subsequent study phases, highlighting some of the key considerations in the TPR adoption and use.

2.2 Study 2: piloting learning designs in a 13-week synchronous hybrid course with all students telepresent

The research question for Study 2 is the following:

> *RQ2*: What factors influence students' sense of social presence and engagement during TPR-mediated participation in classroom activities?

2.2.1 Methods and materials

In the spring semester of 2023/2024, a 13-week hybrid learning course was launched to develop and refine the prototype of a pedagogical design model for the effective use of TPRs in higher education. The participants of this course were also invited to participate in the second 292 stage of this study. In total there were 6 participants (undergraduate students, under 30 years old, 293 3 female and 3 male students). The decision to take part in the study was a voluntary one and it 294 was explained to the students that as such, it did not influence their grades in any way. Building on the findings from Study 1, the course *Enhancing Social Interaction in Education and Business* uses TPRs and allows for testing the practical application of robots in real-world learning environments. The course covered six critical aspects of TPRs' use, laying the foundations for a robust pedagogical design model to guide their integration in teaching. Each week's tasks aligned with one of the six aspects of TPR use: operating environments, educational settings, cognitive and physical limitations, inclusivity and ethics, and instructional methods.

In the first week, the students learned to operate the TPRs, navigating classrooms and open spaces while practicing communicating with both the participants present in the classroom as well as the TPR-mediated students. In subsequent weeks, the students were instructed to adapt the TPRs according to classroom-specific needs, such as conducting vision tests, evaluating content visibility, and presenting lessons. The cognitive and physical limitations of TPRs were also explored through tasks such as using virtual and physical

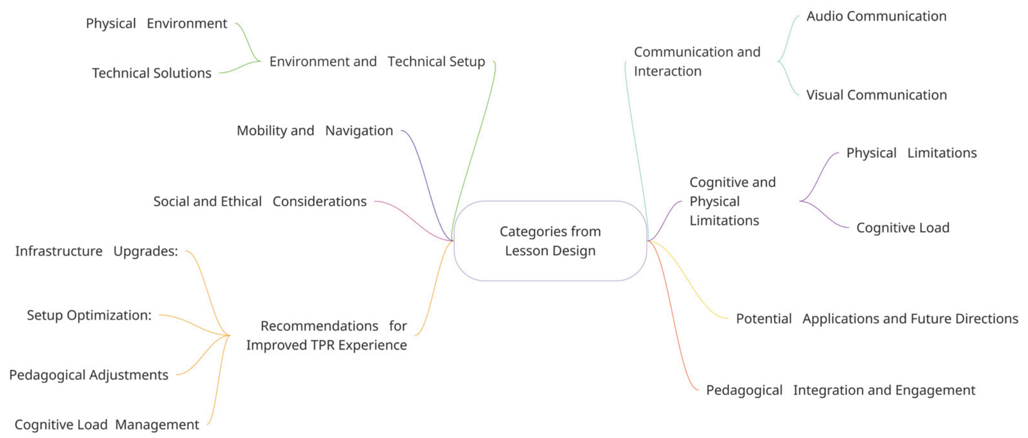

FIGURE 4
Conceptual map of Study 2 Thematical Categories. This conceptual map outlines the critical considerations for lesson design, including environmental and technical setup, mobility and navigation, communication and interaction, cognitive and physical limitations, as well as recommendations for enhancing the TPR experience.

whiteboards, navigating unfamiliar environments, and adapting teaching methods for remote teaching. One week focused entirely on the ethical and cybersecurity dimensions of the use of TPRs. The final week brought the entire content together, with students participating in mini-lectures, collaborative group work, and digital worksheet activities to simulate real classroom dynamics. The students were assigned learning-design-based homework after each lesson, giving them an opportunity to reflect on the lessons and explore the possibilities of using TPRs in similar situations. For example, based on their expressions in the practical session, the students had to analyze the environment (including the technical solution) they had, describe in which learning area they perceived the strongest cognitive overload, reflect on the physical limitations they experienced during the hands-on session, and how they could overcome these limitations. These home assignments (3 from each student) were submitted to thematic content analysis. Microsoft Excel was used for data analysis. Figure 4 illustrates the concept map of the thematic content analysis of the students' homework.

2.2.2 Results: factors influencing students' sense of social presence and engagement during TPR-mediated participation

2.2.2.1 Enhancing the presence

The students reported that they felt a stronger sense of presence and engagement when using TPRs as opposed to standard video conferencing. The sense of presence was strengthened by the TPR's ability to move independently and the opportunity to interact with classmates. One student reflected their own experience: "*Encouraging social interaction in a positive environment and respecting ethical boundaries of the interaction, like privacy and etiquette, are all crucial factors in encouraging a communicative situation. In a productive communicative situation, the benefits of TPRs for (non-verbal) communication can be utilized, making them more useful for learning than a traditional video conference.*" (Student A) A sense of deeper engagement was supported by using digital collaboration tools during group assignments, where TPR-mediated students could actively contribute to teamwork. Another student observed: "*Social interactions are a fundamental part of learning, offering opportunities for collaboration and discussion*." (Student B).

2.2.2.2 Lowering cognitive load

Student reflections revealed that working with multiple open windows during a class increases cognitive load, especially when using a single monitor with limited screen space, as it risks breaking the visual connection with the classroom. One participant reported: "*I perceived the strongest cognitive overload in the first experiment, where I had to split my attention between Zoom with PowerPoint and the TPR user interface*" (Student A). Expanding the computer desktop with an additional monitor made it possible to maintain a virtual connection to the classroom while keeping other necessary applications visible. Combining digital learning materials such as worksheets with TPR-mediated substitutes to paper learning materials helped students reduce their cognitive load and supported gaining deeper understanding of the material. The students also mentioned installing an additional 360-degree camera to provide a better overview of the classroom, improving the perception of the classroom environment. One student suggested further opportunities to lower cognitive load in the following manner: "*I would also recommend using an Owl 360* view camera to keep the overview of noise and movement in the classroom*." (Student A) Creating predefined classroom maps, including marking important locations, helps reduce the strain associated with TPR navigation. A student noticed: "*Moving with a map provided a gratifying and smooth driving experience with much less cognitive load.*" (Student A) When multiple users simultaneously use the same TPR, it is crucial to agree on the distribution of roles.

2.2.2.3 Ethics and cybersecurity

The students identified particular ethical and cybersecurity concerns. Issues may arise because the TPR camera is more mobile

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and, in some models, even better than the human eye. There is also a risk that through the TPR a student may gain unauthorized access to confidential information. Another potential threat is access via active TPR links that were not properly deactivated. The students emphasized the importance of maintaining a respectful attitude toward TPR users. One student noted, for example: "*To be ethical, I now need your consent to lift your TPR body across the threshold.*" (Student A). To ensure privacy, the emergence of potential security incidents must be minimized. As another student pointed out: "*If the people using the lab are not careful, a TPR may access some 'secret' or personal information.*" (Student B) The results of Study 2 were used as the principal data for developing the initial version of the PEPCII model (see also Section 4) that was validated in Study 3, and then finalized, based on the results from Study 3.

2.3 Study 3: testing the pedagogical design model prototype: piloting hands-on workshops for teachers

The research question for Study 3 is the following:

> RQ3: Which educational scenarios allow for the productive use of TPRs, and which factors, respectively, contribute to or hinder the effectiveness their use?

2.3.1 Methods and materials

In Study 3, we shifted the focus to preparing teachers for the practical adoption of TPRs in their teaching. The goal was to acquire a broader understanding of the effectiveness and acceptability of TPRs while developing the first version of the PEPCII Pedagogical Design Model for TPR Users. From May to July 2024, we organized a series of 13 workshops, each lasting for 90 min. The workshops were attended by 56 teachers from Estonia and abroad. In the workshops, we offered hands-on experience in using TPRs and also used the robots to gather the participants' perceptions of their use in the actual classroom setting.

Through the workshops we intended to equip the participants with specific basic skills of operating TPRs in an educational context. Conducted in the format of synchronous hybrid sessions, the workshops included both remote presence and in-person elements. The participants joined the workshops using Zoom, while the instructor and their assistants worked from a specially prepared classroom (see Figure 5). The equipment included a 360-degree camera to provide an immersive view of the teaching space and an additional web camera to ensure that the participants could see and follow the instructor clearly. The classroom layout was simplified by removing unnecessary furniture, enabling the TPR's unrestricted movement. A screen and a whiteboard were set at the front of the classroom.

Each workshop was opened with an introductory session, offering a technical overview of TPRs and explaining the structure of training. After that, the participants were given access to a TPR link via Zoom. Following this, a virtual tour was provided. The practical tasks assigned then to the participants included navigating an obstacle course, delivering mini lectures, and interacting with the class. The session concluded with a focus group discussion, where participants reflected on their experience, particularly focusing on their use of TPRs and views on TPR applications.

The workshops were attended by a diverse group of participants, the majority of them working in higher education (71%). A smaller number of the participants had a general education background (27%) and one person (2%) represented early childhood education. While teachers from Estonia constituted the majority (36), participants from the countries such as Cyprus (14), Austria (2), Finland (1), Portugal (1), Greece (1), and Belgium (1) were also present. Focus group interviews were conducted with a total of 43 participants.

Focus group discussions aimed at identifying challenges and opportunities in the use of TPRs were inspired by three open-ended

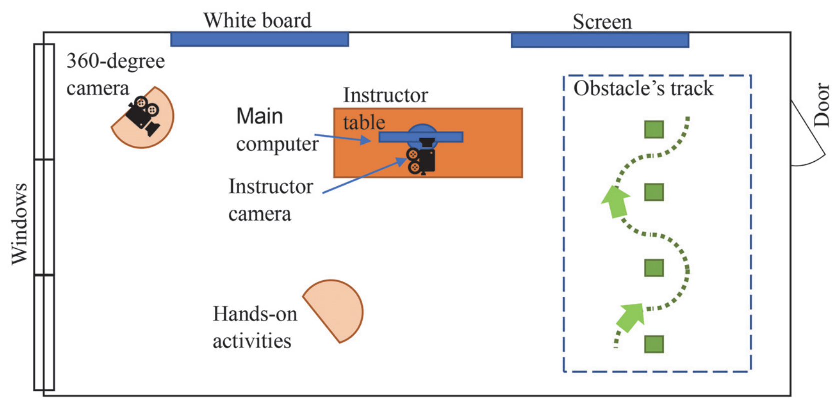

FIGURE 5
Workshop classroom design describes the learning environment in which workshops are conducted. In the front of the classroom, a screen for presenting slides and a whiteboard were placed for use in practical activities. One camera was connected to the instructor's computer and Zoom. The second one was connected to the second computer to provide a 360-degree overview from the classroom to Zoom. The obstacle track was set up in the classroom; arrows indicated the TPRs moving in direction. One classroom side was covered with windows.

FIGURE 6
Conceptual map of Study 3 Thematical Categories. This conceptual map categorizes feedback from workshop focus groups, detailing aspects such as need for support, preparation before class, training, assistant and student preparation, teacher preparation, and other factors including ethical aspects and future directions for TPR development.

questions: Under which circumstances is it appropriate to use TPRs in education? How should the teachers and students involved in TPR-mediated education be prepared for it? What kind of technical and other support does effective use of TPRs require? The discussions were transcribed, anonymized, and analyzed using thematic content analysis. As a result, we developed scenarios for the use of TPRs and listed the factors that contribute to or hinder their effectiveness. Figure 6 illustrates the concept map of the thematic content analysis of focus group interviews.

2.3.2 Results: educational scenarios for the use of TPRs and factors that contribute to or hinder their effectiveness

2.3.2.1 Instances of use

The respondents identified multiple scenarios under which they considered TPR integration justified, including situations where physical attendance might be restricted by illness, injury, or geographic limitations. TPRs were further perceived as beneficial for remote monitoring of collaborative assignments, virtual access to restricted zones such as specialized laboratories with strict biosafety and security requirements, and observation of practical skill acquisition. One participant elaborated on this extended application: "*At that time, I also felt that looking back now on that period of distance learning, especially for music lessons, one big advantage was truly that I could observe more closely how the students hold their instruments or which keys they press, and so on – how their finger positions are and all these kinds of things.*" (P10F).

2.3.2.2 Assistance

The participants reiterated the necessity of having technical support staff available to address logistical demands and emergent hardware or software issues throughout the TPR-mediated instruction. On-site assistance was deemed especially critical for teachers operating the TPR to ensure uninterrupted educational delivery. One respondent explained the need for technical support: "*You need an assistant because, well, the instructor should focus on the educational content and facilitating teaching, not on dealing with one particular person or maybe several, especially if they are present as robots.*" (P29F).

2.3.2.3 Preparation

The teachers emphasized the importance of thorough training and iterative practice sessions to build confidence and aptitude in TPR use. Recommendations included offering blended professional development training, encompassing both online tutorials and in-person workshops to enhance skill acquisition. One teacher stressed that it is important to open the wide variety of possibles TPR uses in education: "*Collecting a lot more possibilities because this is a new technology, and there are hundreds of different ways to use it.*" (P43M).

2.3.2.4 Additional issues

Some participants suggested that there should not be more than 1–2 robots in simultaneous use. One respondent suggested "*I would actually prefer if the school had fewer robots in use, but those robots would be truly high-quality, with a good quality image, adjustable to as short a time delay as possible.*" (P13F) Some participants discussed the ethical perspective of making education accessible. The importance of making additional support available to organizations adopting TPRs was also mentioned. Several participants discussed technical aspects related to the development of TPRs, for example, whether integrating VR solutions in robots might be desirable or whether it would be necessary to further develop the user interface to simplify the use of the robots. One respondent argued that "*The user interface of this telepresence robot is not up to date.*" (P35M).

3 Aggregated results

3.1 The opportunities and limitations of using TPRs in teaching and learning

This study confirms previously noted opportunities of using TPRs, such as enhanced social presence, increased student engagement, and greater flexibility in classroom dynamics, enabling meaningful remote participation in education and providing access to specialized environments (e.g., laboratories). Although many of these opportunities have already been recognized in earlier literature, these results add to the body of literature by recognizing the noted advantages across multiple robot platforms, including the recently released TEMI v3 robot (July 31, 2023). Our results suggest that observed benefits such as enhanced social presence and classroom flexibility are consistent, regardless of specific robot types. As for limitations, the results similarly highlight previously noted technical challenges, such as connectivity disruptions, spatial navigation constraints, and issues related to audio-visual clarity. However, the methodological approach of testing these challenges systematically in this study with multiple TPRs in (including the newest available technology) highlights that the persistence of technical problems is not merely attributable to individual robot models but is inherent in the current state of telepresence robotics technology itself. Recognizing this generalized limitation emphasizes the urgent need for further technological development and targeted improvements to infrastructure if TPR-mediated hybrid learning is to become genuinely scalable and reliable.

3.2 Knowledge, skills, and preparation required from teachers and students to use TPRs effectively

Studies 2 and 3 demonstrate that the effective use of TPRs requires comprehensive preparation from both teachers and students. Teachers need technical skills for operating TPRs, including managing dual screens and troubleshooting basic technical issues. The study also stressed the importance of iterative practice sessions, professional development workshops, and a well-structured model of building up confidence. Students need initial orientation on the operation of TPRs and an understanding of classroom dynamics. Although this result is seemingly similar to ones achieved in previous studies, it highlights that even technologically proficient users, such as PhD students in technical fields, encounter notable challenges when adapting to classroom dynamics via TPRs. It seems that the use of TPRs could demand complex cognitive and situational adjustments, not merely technical competence. Thus, targeted orientation on classroom interaction dynamics is crucial, irrespective of users' technical expertise. In addition, structured support such as on-site technical assistance remains essential to reduce potential disruptions and facilitate smooth, meaningful integration of robots into educational environments.

4 Developing a pedagogical design model

By consolidating the knowledge derived from the review of the state-of-the-art literature and our empirical studies – the interviews, a 13-week hybrid course, and teacher workshops– we designed the final model that is presented as a PEPCII model for the effective use of TPRs. Each of its categories aligns with the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra and Koehler, 2006), while also addressing technology acceptance concerns identified in the broader technology acceptance literature. Table 1 compares the Perifanou (2023) TRinE 4D, Chan et al. (2022) 4C, and the PEPCII model.

The purpose of TRinE 4D is to provide teachers with support for adopting TPRs in teaching and adapting their teaching accordingly. The 4C model offers a hybrid learning framework that enables flexible and active communication through technology, including using TPRs. As a distinct advancement from the previous models, the PEPCII pedagogical design model reveals that in addition to the technical aspects, the use of TPRs in hybrid learning must address the importance of ethical concerns and the systematic need to support teachers and students in their use of TPRs. To provide a better learning experience and improve the quality of learning, cognitive and physical limitations must also be considered. In summary, the PEPCII model offers a broader approach to effectively adopting TPRs, and as it addresses both technology and pedagogy aspects, it can help to create higher-quality and more inclusive hybrid learning environments.

In addition, as compared to the TRinE 4D and 4C models, the PEPCII model emphasizes some of the particularly critical aspects

TABLE 1 Comparisons of TRinE 4D, 4C and the PEPCII model.

Aspects\models	TRinE 4D pedagogical model Perifanou (2023)	4C model for Hyflex classrooms Chan et al. (2022)	PEPCII pedagogical design model
Focusing	Using TPRs in Education	Organizing hybrid learning (HyFlex)	Using TPRs in synchronous hybrid learning
Model components	Four level process	Four main components	Six main components
	1. Define (analyze information about the subject and students) 2. Describe (describe the number of participants involved via TPR, the role of TPR-mediated participants, and the types of TPR) 3. Decide (select teaching methods and tools) 4. Design (plan the process)	1. Content (teaching materials) 2. Collaboration (active learning through collaboration) 3. Community (presence and sense of belonging) 4. Communication (interaction with the teacher and other students)	1. Physical operational and Educational Environment 2. Ethical and Cybersecurity Considerations 3. Pedagogical Integration 4. Cognitive and Physical Limitations 5. Inclusive Access and Engagement 6. Instructional Methods
Educational context	Defines the course topic, learning objectives, student profile	The needs of the students define the use of materials and methods	The physical and virtual learning environments importance (including preparation) is emphasized
Operational Objective	Support teachers in designing activities and lessons that involve TPR.	Offers learners a choice of how to participate in class (physically or virtually).	Enable social presence in synchronous hybrid learning situations.
Applicability	Suitable for situations where physical presence is not possible, but participation is necessary.	Flexible use in different educational contexts (lectures, seminars).	Suitable when the presence is limited (e.g., geographical distance), but active participation and interaction are necessary.

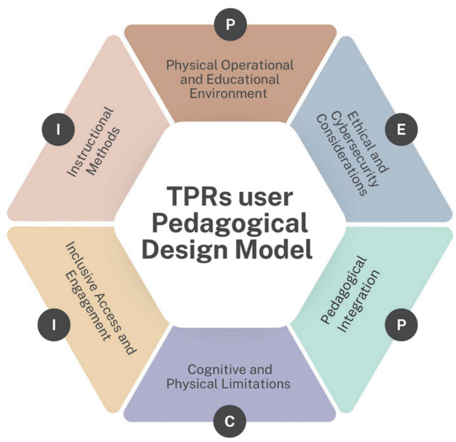

FIGURE 7
Visualizes the components of the PEPCII Pedagogical Design Model for TPR users.

related to adopting TPRs as an emerging technology, drawing attention to ethics, student engagement, and high cognitive load. TRinE 4D and 4C primarily focus on teaching strategies and collaboration in hybrid environments, while overlooking data protection and equitable access issues. The PEPCII model explicitly raises the issues of ethics and cybersecurity to mitigate the risks arising from these domains and to ensure the responsible use of technology. It also addresses potential problems associated with cognitive load, which are often neglected as the primary focus tends to be on the planning and organization of learning activities. The PEPCII model brings challenges related to cognitive load into focus and offers potential remedies. By applying the PEPCII model to TPRs, we ensure their sustainable and effective use in hybrid learning.

As a result of the study, the PEPCII model that stands for Pedagogical Design Model for Integrating Telepresence Robots in Synchronous Hybrid Learning was developed. PEPCII is an acronym derived from six components (see Figure 7) that pertain to various aspects of using TPRs. The PEPCII model was created based on empirical studies and related literature. Table 2 connects the PEPCII components with our empirical findings and some of the previously published articles. The components of the PEPCII model are the following: (a) Physical Operational and Educational Environment, (b) Ethical and Cybersecurity Considerations, (c) Pedagogical Integration, (d) Cognitive and Physical Limitations, (e) Inclusive Access and Engagement, and (f) Instructional Methods.

4.1 Physical operational and educational environment (P)

This Component of the model consists of two subcomponents. First, it describes the requirements and recommendations for the environment where the TPR operates, including ensuring the highest possible quality of the remote presentation and maintaining focus during the delivery of the lesson. Second, it describes the environment where the TPR moves and operates, addressing the infrastructure readiness for integrating TPRs into the educational process and ensuring the well-being of all individuals involved.

In Study 1, the teachers highlighted that for the effective use of TPR, attention must be paid to the design of the learning environment, including such details as the arrangement of the furniture. The layout of the learning environment affects how actively the TPR-mediated

TABLE 2 Traceability table between PEPCII components, empirical evidence and previously published papers.

PEPCII component	Empirical evidence	Related literature
Physical operational and educational environment (P)	• Recommended technical setup for effective TPR use (study 1) • Suitable classroom layout (study 2) • Simple classroom environment (study 3)	Perifanou et al. (2022) and Chan et al. (2022)
Ethical and cybersecurity considerations (E)	• Participants stressed the importance of ethics and cybersecurity (studies 1, 2 and 3).	Elmimouni et al. (2024)
Pedagogical integration (P)	• Developed and tested instructional designs for TPR-mediated participation (studies 2 and 3)	Mishra and Koehler (2006)
Cognitive and physical limitations (C)	• Limitations in non-verbal communication and speed of robot movement (study 1) • Lowering cognitive load (dual-screen setups, predefined navigation maps, additional visual aids like 360° cameras) (study 2) • Developing skills and proficiency in using TPR (study 3)	Huun and Slaven (2024)
Inclusive access and engagement (I)	• Improved social presence and engagement compared to traditional videoconferencing (Study 2). • Deployment scenarios that offer inclusive participation in learning (study 3).	Fabian et al. (2024)
Instructional methods (I)	• Emphasis on thorough preparation in pilot trials, and iterative training (studies 1 and 3) • Recommended training methods (study 3)	Mascret et al. (2023) and Arthanat et al. (2023)

student can engage with what is happening in the physical classroom through hearing and seeing. One interviewee explained.

Study 2 confirmed the previously mentioned results. The possibility of using predefined maps and mapping paths of the robot's movement helps to reduce the students' cognitive load while navigating the learning environment.

The simplified classroom layout used in Study 3 confirmed that the user experience and satisfaction of the TPR-mediated participant are directly influenced by the setup of the learning environment.

4.2 Ethical and cybersecurity considerations (E)

In Study 2, the students were concerned that the robots' cameras might compromise the privacy of other individuals present in the learning environment. According to some of the students, it is also important to consider ethical questions, such as obtaining consent and being aware of the situation. The students also pointed out potential cybersecurity risks associated with the use of TPRs. For example, that unauthorized use of robots might allow access to confidential information.

The participants in Study 3 emphasized that at the organizational level it is important to consider how to use TPRs in school environments. These observations indicate that ethics and cybersecurity are essential aspects when using TPRs in educational settings.

4.3 Pedagogical integration (P)

The Pedagogical Integration component provides recommendations for designing an educational process that enables participants' active involvement through TPRs, including the use of assessment methods that support learning by means of feedback and adaptive teaching techniques.

Study 2 focused on the pedagogical aspects of using TPRs in a real learning situation over a 13-week period. During the course, the use of TPRs was tested in various active learning formats, including group work. Participating students valued highly the integration of TPRs into teaching.

In Study 3, the participants stressed the need to align the use of TPRs with the expected learning outcomes, while maintaining the importance of flexibility and the use of prepared supportive materials. Based on these insights, we conclude that it is essential to emphasize the importance of instructional design in the use of TPRs in teaching– moving beyond their mere physical presence in the instructional space.

4.4 Cognitive and physical limitations (C)

This component addresses particular cognitive and physical challenges related to the use of TPRs and offers solutions for overcoming some of the related limitations. Regarding cognitive challenges, it highlights the creation of conditions that allow users to focus on learning and teaching, such as designing a user-friendly environment and preparing for participation through TPRs. For physical challenges, it specifies the support a TPR user needs to effectively engage in the learning process remotely.

In Study 2, the participating students noticed cognitive overload when engaging in learning activities through TPRs – especially when they had to use additional learning materials or present something themselves. To reduce the cognitive load, they suggested using multiple monitors and visual aids.

In both Study 1 and Study 3, the participants identified slow navigation and signal transmission delays as issues of concern. The participating teachers pointed out that delays in signal transmission hinder real-time response and dynamic interaction. Based on the above, we argue that addressing physical and cognitive limitations constitutes a significant aspect of the effective use of TPRs in education.

4.5 Inclusive access and engagement (I)

This component of the proposed model covers ensuring equal access to teaching for all participants through the adaptation to diverse learning needs and providing a learning environment that respects cultural differences. All our studies highlighted that using TPRs enables active participation when physical presence is not possible.

In Study 3, the participants saw the potential of using TPRs in special education or for students in rural schools. Based on the above, the use of TPRs ensures better accessibility to education and enhances student engagement.

4.6 Instructional methods (I)

The Instructional Methods' component of our model focuses on particular aspects critical to facilitating the educational process, such as providing clear instructions, offering additional training opportunities, and promoting the visibility of best practices.

In Study 1, the participants emphasized the need for thoughtful lesson planning and the development of backup plans. They considered prior practice, rehearsing the planned activities, equipment checks, and the availability of technical support during the learning process as key to a successful TPR experience.

The participants in Study 3 mentioned that practical workshops and training sessions help to increase teachers' confidence and allow building their competence. According to the participants, the successful adoption of TPRs depends on the availability of training materials, opportunities for experience sharing, and hands-on practice.

Prior research (e.g., Elmimouni et al., 2024) has already suggested that systematically addressing challenges caused by the use of TPRs can significantly improve students' learning experience. Our final study has strengthened this point by demonstrating how explicit instructions on classroom lighting, slide color combinations, recommended TPR speeds, and designated communication channels for immediate technical support can substantially reduce both teachers' and students' cognitive load, thus supporting our step-by-step approach (Kasuk and Virkus, 2024).

The use of the PEPCII model in the adoption of TPRs in education will ensure a systematic approach to improving the quality of synchronous hybrid learning, allowing students to be socially present in the learning environment. Following the recommendations outlined in this article ensures that the use of TPRs in the classroom remains ethical, pedagogically effective, and inclusive for all participants. Accordingly, the PEPCII model supports sustainable technology innovation in education.

5 Discussion

The findings presented in this study demonstrate both the benefits and the complexity of integrating TPRs in hybrid educational environments. By triangulating evidence from the three studies, this research contributes to the existing literature on technology integration (Mishra and Koehler, 2006; Elmimouni et al., 2024; Kasuk and Virkus, 2024) and underscores the importance of developing carefully calibrated pedagogical and technical frameworks for the use of TPRs.

One of our significant findings regarding the adoption of TPRs in education stresses the need to consider more than the mere hardware and software readiness. Educationally effective adoption of robotic technologies in education requires a coordinated approach across multiple domains of knowledge and practice. Although prior models such as TPACK have already revealed the interplay between technological, pedagogical, and content knowledge (Mishra and Koehler, 2006), the current article affirms that operational, cognitive, physical, ethical, and instructional dimensions are equally critical for ensuring effective TPR integration. While the PEPCII model proposed here aligns with the TPACK framework, it is unique in explicitly incorporating considerations covering distinct aspects of physical learning environments and issues such as inclusivity, ethics, and cybersecurity. Teachers' testimonies related to the indispensability of the well-structured support – be it in the form of on-site assistants, carefully prepared classrooms, or professional development workshops – further reflect the iterative nature of technology acceptance processes conceptualized in broader frameworks such as TAM and UTAUT (Arthanat et al., 2023; Mascret et al., 2023).

Consistent with some of the earlier studies, our research confirms that TPR-mediated learning can promote a heightened sense of presence and autonomy as compared to conventional video conferencing tools, thereby mitigating student disengagement in hybrid settings (Kasuk and Virkus, 2024). The results of our Study 2 demonstrate that providing users with low-cognitive-load solutions, for instance, dual-monitor setups and pre-mapped classroom navigation, reduces the time spent on troubleshooting and task-switching, ultimately improving the quality of instruction. Additionally, TPRs' mobility supports spontaneous interaction among the participants and their social presence – outcomes that are particularly germane for remote students who would otherwise have limited access to in-person activities (Huun and Slaven, 2024).

Nonetheless, significant barriers persist. Challenges such as weak internet connectivity, audio-visual disruptions, and limited navigational dexterity suggest a delicate balance between technology's affordances and accompanying constraints (Kasuk and Virkus, 2024). TPR-mediated instruction entails heightened dependence on stable infrastructures and support staff; teachers working under conditions of limited resources may find it difficult to adopt TPRs as extensively as sometimes recommended. Additionally, the novelty of TPR-mediated learning requires ongoing professional development for both teachers and technical support teams, emphasizing the socio-technical nature of technology uptake (Perifanou, 2023).

Moreover, the importance of detailed pedagogical planning cannot be overstated. Participant feedback from our studies 1 and 3 showed that success hinges on aligning TPR functionality with specific educational objectives. Whether delivering synchronous lectures or supporting remote student presence, teachers must proactively plan for their activities to capitalize on the benefits of TPR mobility and camera functionalities. This calls for targeted orientation sessions to explain operational protocols, share digital literacy expectations, and describe the accessibility model. Partial reliance on participants with IT or information-science backgrounds may lead to a higher collective competence of the entire group of participants than what one might expect finding among regular teachers. Future research involving a wider demographic variety of teachers and students can help assess the transferability of our model to other subject areas and across educational levels.

Lastly, ethical considerations, particularly surrounding the issues of security and inclusivity, warrant permanent attention. Study 3 activities and workshop discussions support the view that the use of TPRs in sensitive environments, such as laboratories and other specialized facilities, gives rise to additional complexities related to controlling camera angles, maintaining privacy, and clarifying data-handling protocols. These insights corroborate earlier findings (Elmimouni et al., 2024) that a structured approach to data security, supported by institutional policy, is essential for mitigating potential risks associated with remote access.

In summary, our findings confirm that TPRs offer a promising medium for enhancing synchronous hybrid learning when integrated with systematically developed pedagogical frameworks, sustained technical support, and inclusive policy guidelines. Although TPR deployment can be resource-intensive, strategic planning and gradual professional development substantially alleviate such challenges. The resulting PEPCII model offers a comprehensive lens for researchers, practitioners, and policymakers to interrogate the pedagogical and logistical prerequisites for TPR adoption.

6 Conclusion

The research project described in this article contributes to the growing body of literature on telepresence robots in education by proposing and validating a PEPCII model that offers a structured approach to TPR integration. Building on the already established technology-integration frameworks such as TPACK, SAMR, and TAM, the model addresses the multifaceted nature of TPR use in hybrid learning contexts. Through three studies, the research has captured both the promises and the practical challenges inherent in TPR implementation.

Some of the key outcomes of our research demonstrate that TPR-mediated instruction supports improved presence, facilitates flexible class participation, and extends the physical boundaries of the classroom. However, realizing these benefits requires robust support mechanisms, including on-site technical personnel, careful lesson planning, reliable internet infrastructure, and thorough training for both teachers and students. A consistent theme across our studies has been the necessity of proactively reducing cognitive load – by way of dual-screen setups, comprehensive classroom mapping, and seamless integration of digital tools.

Despite the promising outcomes of the three studies, certain limitations must be acknowledged. First, several technical challenges remained unresolved throughout the research. Participants reported persistent issues such as unstable internet connections, audio delays in large classroom environments, and limited navigational control of the TPRs, particularly in settings with obstacles or cluttered layouts. Even with the implementation of solutions such as dual-screen setups, 360-degree cameras, and pre-mapped classroom layouts, these technical problems occasionally disrupted communication and reduced the level of participants' engagement. For example, delayed voice transmission often impaired real-time discussions, and momentary disconnections negatively affected the continuity of learning sessions.

Second, the prior experience and background of the participants had an impact on study outcomes. Many of the teachers and students involved had prior professional or academic experience in information technology or educational technology. Their familiarity with digital tools and openness to experimentation most likely contributed to the successful adoption of TPRs, and the richness of feedback provided. However, this introduces a potential bias, as these users may have been more inclined to overlook or adapt to technical shortcomings than educators with less technological confidence. As such, the generalizability of the findings to broader, more diverse educational settings may be limited.

However, although the relatively small sample size of six teachers and six students limits the generalizability of our results, the qualitative approach adopted helps to bring out the depth of insight of the participants, offering understanding of specific challenges and opportunities in adopting TPRs in higher education, and informing subsequent larger-scale research and pedagogical design. Future research should explore how these challenges affect populations with lower levels of digital literacy and explore long-term technical reliability and support requirements for sustainable TPR integration across varied educational contexts.

This research provides a practical roadmap for embedding TPRs in academic contexts by synthesizing best practices and addressing common challenges. With continuous refinement, thoughtful instructional design, and collaborative effort among the stakeholders, telepresence robots have the potential to transform hybrid education into an inclusive, interactive, and sustainable learning environment – ultimately enriching the educational experience for remote and in-person students alike.

Data availability statement

The datasets presented in this article are not readily available due to confidentiality agreements, participant privacy concerns, or institutional policies. No data sharing is permitted to ensure the protection of sensitive information. Requests to access the datasets should be directed to tiina.kasuk@taltech.ee.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

TK: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing, Formal analysis.

JL: Conceptualization, Methodology, Supervision, Writing – review & editing, Validation. SV: Supervision, Writing – review & editing.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix 3

Publication III

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Validation of the PEPCII pedagogical design model via telepresence robot use in higher education

Abstract: Telepresence robots (TPRs) have been proposed to enhance the participation of distance students in higher education by enabling real-time interaction in synchronous hybrid settings. However, their use introduces pedagogical, technical, and ethical challenges that are insufficiently addressed by existing technology integration frameworks. This study empirically examines the PEPCII pedagogical design model (PEPCII model) through design-based research conducted in authentic higher education teaching contexts. The PEPCII model was applied as a design-informed framework to guide TPR-mediated teaching and a mixed-method validation process involving teachers, TPR-mediated students, and in-class students. The findings indicate that the learning experiences in TPR-mediated hybrid environments are strongly shaped by teacher preparedness and the deliberate pedagogical integration, while also showing that TPRs can help students participate when they can't attend in person. Drawing on multi-stakeholder empirical evidence, the study refines the implementation of the PEPCII model and articulates practical guidance for applying the model. By basing validation in actual classroom use, the study contributes to research on hybrid learning design and offers a practical framework for addressing persistent challenges in TPR-mediated higher education.

Keywords: telepresence robot; pedagogical design model; hybrid learning

Introduction

Telepresence robots (TPRs) are increasingly used in higher education to enhance the participation of distance students by enabling real-time interaction in shared learning environments (Fletcher et al. 2023). TPRs are remotely controlled mobile videoconferencing devices that allow users to be physically presence in a distant location (Virkus et al. 2023). Despite their potential, the integration of TPRs into teaching and learning presents persistent pedagogical, technical, and ethical challenges. These include audio- and video-quality issues, background noise, restricted fields of view, connection disruptions, and limited access to immediate technical support, all of which can constrain participation and disrupt instructional flow. Teachers have also reported difficulties in managing classroom dynamics and ensuring the meaningful inclusion and well-being of TPR-mediated students (Powell et al. 2021; Leoste et al. 2022; Charteris et al. 2022), highlighting the need for targeted training, deliberate instructional planning, and supportive learning environments (Ahumada-Newhart and Olson 2019; Weibel et al. 2023).

In addition, social and ethical challenges arise when in-class students are uncertain about how to interact with TPR-mediated peers, potentially increasing social distance and reducing participation (Newhart et al. 2016), with implications for student well-being (Newhart and Olson 2017). At the institutional level, high costs, limited infrastructure, and the absence of systematic training or implementation frameworks often place the burden of TPR adoption on individual teachers. Addressing cybersecurity and ethical considerations through explicit guidelines and shared norms has been identified as a way to support responsible and informed participation among all classroom actors (Page et al. 2021).

While established technology adoption frameworks such as the Technology Acceptance Model (TAM) (Davis 1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al. 2003) explain individual acceptance of digital tools, they treat technology largely as a neutral instrument and do not account for the embodied, mobile, and socially visible nature of TPRs. In higher education classrooms, TPRs reconfigure interaction by physically representing remote students and reshaping relations among teachers and in-class peers (Newhart and Olson 2017; Weibel et al. 2023). Although the TPACK framework (Mishra and Koehler 2006) provides a conceptual foundation for technology integration, it offers limited guidance for addressing the pedagogical, ethical, and inclusion-related challenges associated with TPR-mediated learning (Voogt et al. 2013; Gamberini et al. 2022; Dinçer 2024). To address this gap, the PEPCII pedagogical design model (PEPCII model) conceptualises use of TPRs as a learning setup that involves both social and technological elements that integrates pedagogical, environmental, ethical, cognitive, and inclusion-focused dimensions within a single design framework.

In this study, validation refers to the empirical examination of the PEPCII model in authentic higher education teaching contexts. Rather than testing causal effectiveness, validation focuses on establishing the PEPCII model's practical usability, contextual relevance, and capacity to support teachers, TPR-mediated students, and in-class students during real courses. Through design-based research and multi-stakeholder feedback, validation examines the PEPCII model's readiness for operational use and informs its iterative refinement for synchronous hybrid learning environments.

Building on prior research, the PEPCII model is positioned as an operational extension of TPACK for TPR-mediated higher education. While TPACK specifies the knowledge domains required for technology integration, the PEPCII model is applied here as a design-informed framework to examine the preparation, implementation, and enactment of TPR-mediated teaching. The model structures the analysis of practices involving teachers, TPR-mediated students, and in-class students, enabling a systematic examination of how pedagogical, environmental, ethical, cognitive, and inclusion-related considerations shape synchronous hybrid learning experiences.

The study was guided by the following research questions:

RQ1: What factors shape the adoption and effective use of telepresence robots in higher education, from the perspectives of teachers, TPR-mediated students, and in-class students?

RQ2: How do empirical findings from multiple stakeholder groups contribute to the validation and refinement of the PEPCII model in synchronous hybrid learning contexts?

The paper begins with an exploration of existing literature in Section 2, setting the stage for the detailed research methodology Section 3. Section 4 presents the study's findings, which are then analysed in the discussion of Section 5. Section 6 focuses on the refinement of the PEPCII model based on empirical findings, and Section 7 concludes the paper.

Literature review

Synchronous Hybrid learning as a Pedagogical Context

Hybrid learning combines face-to-face instruction with online participation supported by digital technologies (O'Byrne and Pytash 2015). In this study, the focus is on synchronous hybrid learning, in which remote and in-class students participate simultaneously in shared learning activities. Although this configuration aims to enable equitable participation across modalities, prior research consistently shows that it introduces substantial pedagogical, organisational, and coordination challenges (Almusaed et al. 2023). Simultaneous engagement of physically and remotely present students places increased demands on instructional design, classroom coordination, and the management of interaction across learning spaces(Raes et al. 2020).

While synchronous hybrid learning can enhance flexibility and access, its effectiveness depends strongly on how interaction and participation are pedagogically designed (Yu et al. 2022; Liu et al. 2024). Empirical evidence indicates that hybrid learning requires deliberate instructional design to support active learning, communication, and social presence across modalities (Müller et al. 2023). However, recent studies highlight persistent risks associated with synchronous hybrid learning, including reduced social presence, unequal participation, and the marginalisation of remote students when interaction is not intentionally structured (Fabian et al. 2024). A systematic review of educators' experiences further demonstrates that instructors often struggle to balance attention between in-class and remote students, leading to increased workload and interactional asymmetries (Wood et al. 2025). Research on self-regulated learning suggests that while student-level strategies can support engagement in blended contexts, they cannot compensate for structural and pedagogical shortcomings in synchronous hybrid environments (Luo and Zhou 2024)

These limitations point to the need for pedagogical approaches that extend beyond conventional videoconferencing tools, particularly about visibility, interaction, and social presence in shared learning spaces.

Telepresence Robots in Synchronous Hybrid Learning

TPRs enable participation in physical learning environments from a distance by allowing users to be embodied and mobile participants via remotely controlled videoconferencing systems (Tsui et al. 2011; Kristoffersson et al. 2013; Jakonen et al. 2025). Compared to fixed videoconferencing setups, TPR mobility reconfigures visual access and interaction by granting remote students greater control over what they see and attend to in the classroom (Hu et al. 2024; Jakonen et al. 2025).

TPRs have been used to support the reintegration of homebound and chronically ill students into the learning process (Ahumada-Newhart and Olson 2019; Weibel et al. 2024; Neumann et al. 2025) while also expanding opportunities for language learning (Tanaka 2014; Jakonen et al. 2025), medical and professional education (Rudolph et al. 2017), and synchronous hybrid learning in higher education (Perifanou 2023). More recent research situates TPRs within emerging cyber-physical learning environments that seek to integrate remote and in-class students into a shared pedagogical space (Sockalingam et al. 2025).

Empirical studies suggest that the use of TPRs can enhance remote participants' engagement agency, and both social and physical presence compared to screen-based participation (Leoste et al. 2022; Häfner et al. 2023; Hu et al. 2024; Kasuk et al. 2025a). TPRs have also been shown to support inclusive participation for students with physical disabilities, injuries, prolonged illness, or anxiety-related barriers to in-person attendance (Weibel et al. 2023; Neumann et al. 2025).

At the same time, the educational use of TPRs is accompanied by persistent technical spatial, and interactional. These include connection instability and latency (Weibel et al. 2023; Leoste et al. 2024) difficulties related to navigation and positioning within the classroom spaces (Gamberini et al. 2022; Kasuk et al. 2025b; Zand and Arif 2025), and fluctuations in audio visual quality that affect turn-taking and mutual understanding (Elmimouni et al. 2023). Studies further indicate that without deliberate pedagogical support, remote students may experience reduced participation, interactional asymmetries, or marginalisation in group activities (Fabian et al. 2024; Asadi and Fischer 2025). Consequently, effective integration of TPRs requires not only reliable technical infrastructure but also pedagogical preparation, shared interactional norms, and intentional design of inclusive participation structures addressing visibility, turn allocation, and social presence (Leoste et al. 2022; LeTendre and Gray 2024; Asadi and Fischer 2025)

Taken together, research on TPRs demonstrates that their educational value depends not only on technical functionality but on how participation, interaction, and inclusion are pedagogically designed, dimensions that are only partially addressed by existing pedagogical and technology adoption frameworks.

Limits of Existing Pedagogical and Technology Adoption Frameworks

Although technology adoption frameworks have been widely used to study digital tools in education, they offer limited guidance for addressing the embodied and relational dimensions of TPR-mediated learning. Models such as the TAM (Davis 1989), and the UTAUT (Venkatesh et al. 2003), focus primarily on individual perceptions of usefulness, ease of use, and behavioural intention, conceptualising technology largely as a neutral instrument. As such, they do not sufficiently account for the embodied, mobile, and socially visible nature of TPRs or for the shared control between people and technology that characterises TPR-mediated classrooms, where interaction is reshaped among teachers, remote students, and in-class peers (Scherer et al. 2019).

Prior research on technology integration in teacher education demonstrates that even when teachers possess basic ICT literacy, they often lack the curricular and pedagogical competencies required to translate technological knowledge into situated instructional practice, particularly in complex learning environments (Dinçer and Çengel-Schoville 2022)

TPACK framework (Mishra and Koehler 2006) provides a more comprehensive foundation by integrating technological, pedagogical, and content knowledge. However, empirical research indicates that teachers frequently lack the design-level competencies required to translate this knowledge into pedagogical practice (Dinçer 2024). TPACK also offers limited guidance for addressing challenges specific to TPR-mediated learning, such as managing physical classroom space, negotiating ethical and privacy concerns (Voogt et al. 2013), or mitigating the cognitive and physical demands associated with robot-mediated participation (Gamberini et al. 2022; Weibel et al. 2023). Moreover, the framework implicitly assumes that teachers retain primary control over technology integration, whereas agency in TPR-mediated environments is distributed across human and technological actors.

Compared with more narrowly focused pedagogical models such as the TRinE model (Perifanou 2023) and the 4C model (Chan 2024), which primarily emphasise instructional structuring, the PEPCII model conceptualises the use of TPRs as a learning setup that involves both social and technological elements. It integrates pedagogical, environmental, ethical, cognitive, and inclusion-related dimensions within a single design framework, thereby responding more directly to the complex realities of synchronous hybrid learning with TPRs. As summarised in Table 1, technology acceptance models such as TAM and UTAUT offer limited guidance for TPR-mediated hybrid learning, as they do not account for embodied presence or shared control between people and technology.

Table 1
Comparative overview of pedagogical frameworks relevant to TPR-mediated hybrid learning

Framework	Primary focus	TRL maturity	Key limitation
TAM	Technology acceptance	Low	Treats technology as neutral; ignores embodied and social presence
UTAUT	Use intention and social influence	Low	Does not address classroom interaction or shared control between people and technology
TPACK	Integration of technological, pedagogical, and content knowledge	Moderate	Conceptual rather than design-operational
TRinE / 4C	Structured pedagogical interaction design	Moderate	Limited treatment of ethics, space, and inclusion
PEPCII	Pedagogical design for learning environments integrating social and technological elements	High	Validated primarily in higher education contexts

This comparison highlights the need for a design-oriented framework such as the PEPCII model that explicitly addresses the embodied, ethical, and relational dimensions of TPR-mediated hybrid learning.

Methodology

Methodology and materials

The present study builds explicitly on the previously developed the PEPCII model, which was derived through a multi-phase empirical research process involving teacher interviews, a semester-long synchronous hybrid course, and hands-on workshops with primally higher education teachers. In that earlier work, the PEPCII model was constructed as a comprehensive pedagogical design model addressing six interrelated dimensions critical to TPR-mediated synchronous hybrid learning: the physical and operational environment, ethical and cybersecurity considerations, pedagogical integration, cognitive and physical limitations, inclusive access and engagement, and instructional methods (Kasuk et al. 2025c) While the development study established the conceptual structure and internal coherence of the PEPCII model, it also explicitly called for further validation through sustained implementation in authentic higher education contexts and multi-stakeholder feedback.

Accordingly, the current study does not aim to redesign or reconceptualise the PEPCII model, but to validate its ready for practical use and practical applicability when enacted in real instructional settings. This positioning aligns with prior research demonstrating that technology integration frameworks require curricular and design-level operationalisation to be effective in real instructional contexts (Dinçer and Çengel-Schoville 2022). To achieve this, Technology Readiness Levels (TRL), originally developed by NASA in the 1970s, constitute a nine-level framework for assessing the maturity and ready for practical use of technologies, providing a structured method to evaluate their applicability in diverse disciplines, including education (Artyukhov et al. 2021). While initially applied in aerospace , TRLs have been adapted to evaluate educational models, providing a structured strategy to assess their readiness from conceptualisation to real-world development (Artyukhov et al. 2021). TRL is used in this study as an analytical validation lens to examine the ready for practical use of the PEPCII model.

Previous research demonstrates that TRL can be adapted to educational contexts by providing a framework to assess and the maturity of intangible systems like higher education quality frameworks, teaching projects, and learning solutions, ensuring they are effectively implemented in real-world educational environments. TRL-based approaches have been applied to evaluate institutional readiness and quality assurance systems in higher education (Artyukhov et al. 2021), as well as the maturity of educational and social science research projects implemented in practice (Cobos et al. 2021). Studies in educational technology further indicate that higher TRL levels correspond to validation through sustained real-world educational use rather than experimental development, underscoring the methodological relevance of TRL for field-based educational research (Cervinska et al. 2022). Complementary readiness-oriented models, such as Education Readiness Levels (ERLs), similarly conceptualise readiness as the validated implementation of educational courses and training modules in practice (Dinda et al. 2017).

In this study, the analysis is explicitly limited to TRL 7–9, which correspond to demonstration in operational environments, validation in real use, and confirmed operational readiness. This positioning frames the PEPCII model as a pedagogical design framework validated through authentic instructional implementation and multi-stakeholder feedback rather than as a conceptual or technical prototype.

The authors conducted the TRL 7-9 assessment by systematically reviewing the empirical implementation evidence. The TRL framework applied follows the definitions used within the Horizon Europe programme of the European Commission, under which the EdTech Talents project (Project No. 101119689 – HORIZON-WIDERA-2022-TALENTS-03) is funded. Within the framework of the EdTech Talents project, a consensus-based evaluation procedure was conducted by the project steering committee to assess the maturity of the developed educational technology approach against Technology Readiness Level (TRL) indicators derived from the NASA Technology Readiness Level definitions. The steering committee included senior representatives from the consortium institutions: Tallinn University of Technology, University of Novi Sad (Faculty of Technical Sciences), Óbuda University, Johannes Kepler University Linz, Rey Juan Carlos University, and Bielefeld University, together with representatives from educational technology companies from Estonia, Serbia, Germany, Austria, Hungary, and Spain.

The evaluation applied the established Technology Readiness Level (TRL) framework originally developed by NASA to assess the maturity of technological innovations. The TRL framework defines nine sequential levels of technological readiness, ranging from basic scientific principles (TRL 1) to fully operational systems proven in real-world environments (TRL 9). At TRL 1, basic scientific principles underlying a concept are observed and reported, typically through peer-reviewed research. TRL 2 involves the formulation of a technology concept or application, where potential practical use is identified but remains largely speculative. At TRL 3, analytical and experimental studies provide proof of concept, demonstrating critical functions or characteristics through modelling, laboratory testing, or simulation. TRL 4 requires validation of key components or subsystems in a laboratory environment, often through low-fidelity prototypes or integrated software elements. TRL 5 involves validation of components or prototypes in a relevant environment that simulates operational conditions and demonstrates expected performance. At TRL 6, a system or subsystem prototype is demonstrated in an operational or near-operational environment, confirming engineering feasibility and functional performance. TRL 7 requires demonstration of a system prototype in an actual operational environment with most functional elements integrated. TRL 8 indicates that the complete system has been tested, validated, and qualified for operational use, with full documentation and verification completed. Finally, TRL 9 represents a fully mature technology that has been successfully deployed and proven in real operational conditions through sustained use and documented performance outcomes.

In this study, the steering committee reviewed empirical evidence from the implementation of the PEPCII model in synchronous hybrid higher education and mapped the observed results against the relevant TRL indicators. The assessment considered documented analytical results, experimental validation, prototype implementation in real educational settings, and operational performance evidence generated during the project activities. The TRL indicators used for verification included criteria related to conceptual formulation, analytical validation, prototype demonstration, and operational testing, as defined in the NASA Technology Readiness Level framework.

The final TRL classification was determined through a structured consensus process among the steering committee members. Each participating institution reviewed the available empirical evidence and documentation from the implementation studies, after which the committee jointly determined the technology maturity level that best corresponded to the observed performance and validation results according to the NASA TRL definitions.

For each TRL stage, the standard descriptors (demonstration in an operational environment; validation in real use; proven operational readiness) were compared with documented characteristics of PEPCII implementation, including course deployment, stakeholder feedback, and theoretical alignment. TRL levels were assigned once consensus was reached that the empirical evidence satisfied the criteria adapted to the educational context, reflecting operational readiness within the investigated higher education contexts rather than universal generalisability beyond comparable synchronous hybrid learning environments.

The empirical materials considered in this assessment included documented course implementations across two universities, focus group transcripts from teachers and TPR-mediated students, written responses from in-class students, and observed consistency of findings across courses and semesters. To ensure methodological transparency and auditability, Table 2 presents the operationalisation of TRL 7-9 within the validation of the PEPCII model, mapping each level to its educational interpretation and corresponding empirical evidence.

Table 2
Operationalisation of TRL 7–9 in the validation of the PEPCII model

TRL level	TRL criterion (Horizon Europe)	Operational indicator	Empirical evidence used
TRL7	System demonstrated in an operational environment	Implementation of the PEPCII model in authentic higher education courses involving TPR-mediated participation	Implementation across 14 courses at two universities; documented classroom use of TPR-mediated participation
TRL 8	System completed and validated in real-world use	Multi-stakeholder validation of the model during and after course implementation	Focus group interviews with teachers and TPR-mediated students; written interviews with in-class students; triangulated qualitative analysis
TRL 9	System proven in operational use	Evidence of sustained usability and stable pedagogical functioning across courses and contexts	Consistent findings across courses and semesters; alignment with established pedagogical frameworks; component-level refinements without changes to the conceptual structure of the model

Within the framework of this study, the compliance of the PEPCII model with TRL 7 was assessed across 14 courses conducted over two academic semesters at two universities. TRL 8 was evaluated through the triangulation of feedback collected via focus groups and written interviews from three stakeholder groups, teachers, TPR-mediated students, and in-class students. TRL 9 was assessed by examining indicators of sustained usability across different courses and institutional contexts. In addition, the alignment of the empirical findings with established pedagogical frameworks was examined. Within the investigated contexts, the PEPCII model met the criteria corresponding to TRL 9. The improvements to the model identified during validation remained at the component level and were not conceptual. Consistent patterns were observed across courses and cohorts.

The analysis is further informed by specific educational theories, such as Cognitive Load Theory and instructional design principles, which help structure the analytical dimensions of the PEPCII model by providing a framework for understanding how these components function in practice. Rather than functioning as parallel or competing theoretical frameworks, these theories are used as interpretative lenses to operationalise the PEPCII model components and to guide the coding and interpretation of empirical data across stakeholder groups. Positioning the PEPCII model at TRL 9 refers to its demonstrated stability and sustained use within the investigated higher education contexts and does not imply universal generalisability beyond comparable synchronous hybrid learning environments.

Table 3 provides a synthesis of the pedagogical dimensions based on educational theories that guide the data analysis. The described dimensions created a coherent coding logic to examine how the components of the PEPCII model manifest themselves in operational use and support the validation of the PEPCII model in the real-world learning and teaching process.

Table 3

Pedagogical dimensions and educational theories guiding the analytical framework

Pedagogical dimension	Key theoretical foundations	Analytical indicators	Related PEPCII components
Cognitive load & usability	Cognitive Load Theory (Sweller 1988), Technology Acceptance Model (Davis 1989)	Audio intelligibility, camera focus stability, perceived effort to follow instruction	C – Cognitive and physical limitations
Instructional alignment	Constructive Alignment (Biggs 1996), SAMR Model (Puentedura 2006)	Suitability of TPR-mediated participation for specific learning activities	P – Pedagogical integration
Digital readiness & support	Zone of Proximal Development (Vygotsky 1978), Technology Readiness Index (Parasuraman 2000)	Availability and clarity of preparation materials, adequacy of initial onboarding and guidance	C – Cognitive and physical limitations; I – Instructional methods
Presence & engagement	Community of Inquiry Framework (Garrison et al. 1999), Social Presence Theory (Short et al. 1976)	Teachers' inclusion strategies, opportunities for interaction, frequency and quality of participation of TPR-mediated students	I – Inclusive access and engagement
Equity & ethical inclusion	Universal Design for Learning (CAST 2024), Digital Ethics by (Floridi et al. 2018)	Visibility of TPR-mediated students, privacy and consent awareness, perceived fairness in group interactions	E – Ethical and cybersecurity considerations; I – Inclusive access and engagement
Motivation & self-regulated learning	Self-Determination Theory (Deci and and Ryan 2000), Self-Regulated Learning (Zimmerman 2002)	Student autonomy, effort required to participate via a TPR, expectation management regarding limitations and benefits	I – Inclusive access and engagement; C – Cognitive and physical limitations
Instructional methods	Instructional design principles (Merrill 2002) and (Gagné 2005); Zone of Proximal Development by (Vygotsky 1978)	Clarity of instructional guidelines, availability of exemplars and demonstrations, adequacy of teachers and student training for TPR-mediated instruction	I – Instructional methods
Technology integration	Technological Pedagogical Content Knowledge (TPACK) (Mishra and Koehler 2006)	Coherence between technological functionality, pedagogical decisions, and subject content in TPR-mediated teaching	P – Pedagogical integration

The analytical dimensions outlined above, which include factors such as cognitive load and instructional design, were applied consistently across all stages of empirical work to ensure a comprehensive evaluation of the PEPCII model. The following section describes the study context, sample and data collecting and analysing procedures.

Data collection and analysis

This study adopted a design-based research (DBR) orientation as a design-informed methodological stance for examining teaching and learning in authentic higher education contexts. DBR is understood in line with its foundational conception as an emerging paradigm that integrates the study of learning processes with the design and examination of interventions in real-world settings, while allowing flexibility in how design cycles are enacted (Baumgartner et al. 2003).

DBR was not employed to drive repeated cycles of intervention redesign. Instead, it was used to examine and validate how the PEPCII model functioned when applied in courses involving TPR-mediated participation. The PEPCII model operated as a design intervention guiding instructional preparation and enactment, while empirical data informed component-level refinement and validation of the PEPCII model.

Recent systematic reviews indicate that DBR practice is methodologically diverse and does not uniformly involve iterative redevelopment. Many DBR studies prioritise contextual analysis, validation, and the articulation of design principles over repeated redesign, particularly in complex and naturalistic educational settings (Tinoca et al. 2022). This is especially suitable in higher education, were institutional constraints and multi-stakeholder contexts limit opportunities for controlled reimplementation.

Accordingly, the study employed a pragmatic, field-based design-based research orientation to examine implementation and stakeholder feedback, focusing on design tensions and refinement needs rather than iterative instructional redesign (Cochrane et al. 2023). As illustrated in Figure 1, the DBR orientation links design-informed preparation, authentic implementation, and reflexive analysis, culminating in the validation of the PEPCII model. This approach aligns with core DBR principles of grounding theory in practice and generating transferable design knowledge, while foregrounding validation over iterative redesign (Baumgartner et al. 2003; Tinoca et al. 2022).

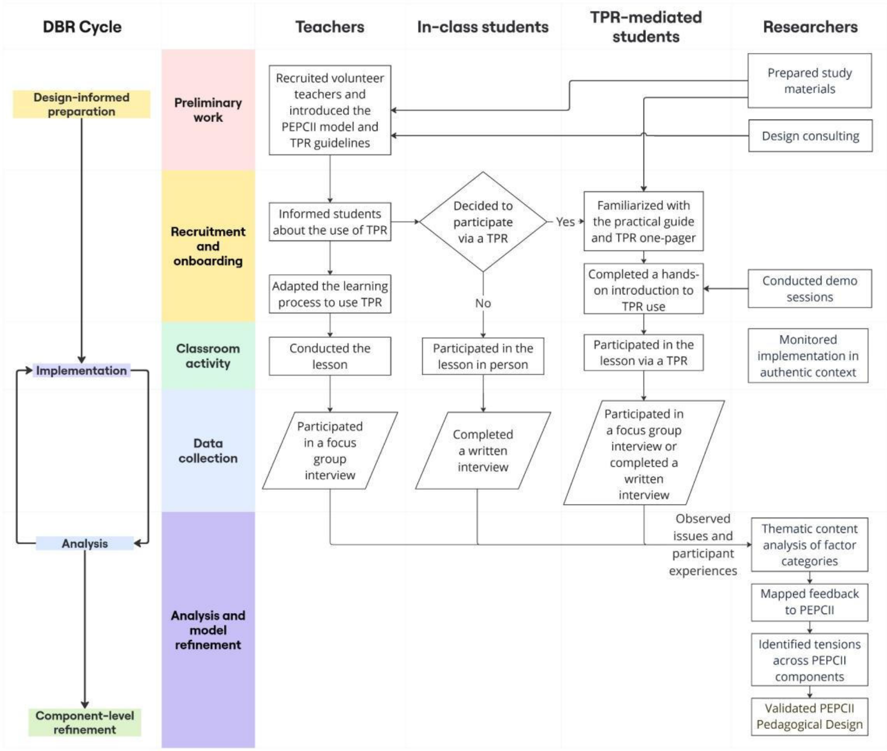

Figure 1. Design-based research workflow for validating the PEPCII pedagogical design model.
The diagram illustrates the design-based research (DBR) workflow involving teachers, in-class students, TPR-mediated students, and researchers. The process includes design-informed preparation, recruitment and onboarding, classroom implementation, multi-stakeholder data collection, and reflexive thematic analysis leading to component-level refinement and validation of the PEPCII model.

Volunteer teachers were recruited and introduced to the PEPCII model and TPR guidelines. Students were informed, onboarded for TPR participation, and teaching was implemented in authentic instructional contexts, after which multi-stakeholder data informed model validation and refinement.

The focus group interview protocols and written interview questions are provided in Appendix 1. All questions were aligned with the PEPCII model, with a detailed mapping of interview items to model components presented in Appendix 2. Additional supporting documentation used during data collection and analysis, including the multi-user control protocol derived from empirical findings, is provided in Appendix 3.

Ethical considerations, informed consent and data management

The study was conducted in accordance with the principles of responsible research and research integrity outlined in the Estonian Code of Conduct for Research Integrity, a national policy document governing responsible research practices in Estonia (01 January 2023; ISBN 978-9985-4-1353-1), developed by the Estonian Research Council and published by the Centre for Ethics, University of Tartu. Tallinn University of Technology, the institution leading the research presented in this article, is a signatory to this national policy framework. Based on the nature of the study and applicable institutional policies, the research was assessed as not requiring formal institutional ethics committee approval. The study involved voluntary participation, and informed consent was obtained from all participants prior to data collection. All collected data were anonymised and handled confidentially. No personally identifiable information was retained. Data were securely stored and used solely for research purposes, with access restricted to the research team, and will be retained only for the period necessary to complete the research and publication process before secure deletion.; therefore, no ethics approval ID was issued.

In accordance with the principles outlined in the *Estonian Code of Conduct for Research Integrity*, a national policy document governing responsible research practices in Estonia, informed consent was obtained from all participants. Informed consent is understood as a process whereby a person voluntarily agrees to participate in research after receiving and understanding sufficient information about the study. Participants were initially contacted via email and provided with information about the research objectives, procedures, use of collected data, and the intended dissemination of results. Participants confirmed their willingness to participate by replying to the email indicating their agreement.

Participation in data collection was voluntary for all participant groups, including teachers, TPR-mediated students, and in-class students. At the start of each focus group interview, participants were orally informed about the purpose of the study, the voluntary nature of participation, their right to withdraw without consequences, and the recording of the session. They were informed that the data would be used in anonymised form to examine the implementation of the PEPCII model in synchronous hybrid higher education and that a scientific article would be published based on the data. Participants were also informed that fully anonymised research materials may be shared via a research data repository in accordance with applicable data protection regulations. After presenting this information, the interviewer requested consent, and audio recording commenced only after consent was obtained.

For written interviews conducted via MS Forms, an introductory explanation of the study and data processing procedures was presented at the beginning of the questionnaire. This information included the study's purpose, voluntary participation, data processing procedures, the use of anonymised data in scientific publications, and the potential sharing of anonymised materials via a research data repository. Completing and submitting the questionnaire constituted informed consent.

Data protection and confidentiality were ensured throughout the research process. Audio recordings were stored on a password-protected computer requiring user authentication and were accessible only to the author who conducted the data collection and transcription. Recordings were permanently deleted after transcription was completed and verified. Anonymisation was carried out during transcription, with all identifying information removed or replaced with pseudonyms (e.g., T01, S04, C12). No direct personal identifiers were retained in the analytical dataset.

Participants and study context

Three participant groups were involved: (1) teachers delivering courses with TPR-mediated participation, (2) students attending remotely via TPRs (TPR-mediated students), and (3) students physically present in the classroom (in-class students). Across all groups, 726 individuals were eligible to participate, of whom 113 contributed data. Data collection involved two qualitative instruments: focus group interviews and written interviews. The written interviews were administered at the end of the course.

Among teachers, 10/16 (62.5%) took part, all through focus group interviews (3 male, 7 female). Of the 52 eligible TPR-mediated students, 27/52 (51.9%) took part (8 male, 19 female); 17 contributed via focus group interviews and 10 via written interviews. In-class students constituted the largest stakeholder group: 78/658 (11.9%) completed end-of-course written interviews (41 male, 33 female, and 4 who preferred not to disclose gender).

Across all groups, 113/726 eligible participants contributed data (15.6%). The distribution of participants and responses across stakeholder groups and data collection instruments is presented in Table 4.

Table 4
Participant groups and participation rates by data collection method

Participant group	Eligible participants (N)	Focus group interviews (n)	Written interviews (n)	Total participants (n)	Participation rate (%)
Teachers	16	10	–	10	62.5%
TPR-mediated students	52	17	10	27	51.9%
In-class students	658	–	78	78	11.9%
Total sample	726	27	88	113	15.6%

Note. Focus group interviews were conducted with teachers and TPR-mediated students. Written interviews were completed by TPR-mediated students and in-class students at the end of the course.

No additional demographic variables were collected, as the analytical focus was on validating the PEPCII model across stakeholder roles rather than on population-level comparisons.

Design-informed preparation and implementation

In line with the first phase shown in Figure 1, volunteer teachers were recruited through email invitations and introduced to the PEPCII pedagogical design model and the TPR guidelines. This design-informed preparation constituted the initial intervention guiding subsequent instructional planning.

Following this familiarisation, participating teachers informed students about the opportunity to participate in the course via a TPR. The student notification included a brief explanation of TPR use, key considerations for participation, and a concise one-page guide outlining basic control procedures.

Students who expressed interest contacted a designated support person. They familiarised themselves with the practical guide and one-page TPR instructions and subsequently completed a hands-on TPR introduction in the classroom or relevant learning environment. During this onboarding, students received access details and practical guidance for joining the course via a TPR, corresponding to the onboarding steps depicted in Figure 1.

All courses were conducted using the TEMI V3 TPRs. Teaching activities included lectures, seminars, and practice-based sessions implemented in authentic instructional contexts. Depending on course design and technical constraints, up to ten students could connect to a single TPR simultaneously, as reflected in the implementation phase of Figure 1.

Data collection aligned with stakeholder roles

As indicated in Figure 1 and specified in Table 4, data collection occurred during and after course implementation and was tailored to each stakeholder group. Teachers participated in three focus group interviews conducted between October and December 2024, focusing on pedagogical preparation, instructional enactment, and the integration of TPR-mediated students. Telepresence participants contributed through eight focus group interviews during the same period and through written interviews administered in May 2025 following course completion. In-class students provided feedback exclusively through end-of-course written interviews addressing inclusion, interaction, and ethical aspects of shared classroom participation. Because the focus group interviews and written interviews were conducted at different points in the course timeline, some degree of recall bias cannot be entirely excluded. However, the written interviews were administered immediately after course completion and focused on concrete course experiences, which helps to minimise potential retrospective distortion.

All focus group interviews were conducted by one of the authors via MS Teams. With participants' consent, interviews were audio-recorded and transcribed using the online transcription tool *tekstiks.ee* (Olev and Alumäe 2022), followed by manual error correction. Written interviews were administered through an online survey created in MS Forms and distributed by course instructors at the end of the course. Triangulation of data from teachers, TPR-mediated students, and in-class students corresponds to the multi-perspective feedback loop depicted in Figure 1 and supports the validation logic outlined in Table 4.

Triangulating data from teachers, TPR-mediated students, and in-class students corresponds to the multi-perspective feedback loop depicted in Figure 1 and supports the validation logic underlying Table 4.

Data analysis and model validation

Qualitative data from focus group interviews and written responses were analysed using a reflexive thematic analysis approach (Smith 1992). Initial coding was inductive and data-driven, proceeding through repeated close reading of transcripts to identify recurrent experiences, concerns, and enabling conditions related to TPR-mediated teaching. Coding remained semantic and experiential and was applied consistently across all data sources to enable systematic comparison between stakeholder groups.

The analysis followed a staged process: meaning units were coded line-by-line, clustered into candidate categories through constant comparison across data sources and consolidated into higher-order themes. Analytic memos documented interpretive decisions, emerging tensions, and links between empirical observations and the study context. One author conducted the primary coding, while a second author reviewed the developing code structure and thematic interpretations.

Divergences were discussed until conceptual agreement was reached, supporting analytical rigour through reflexive dialogue rather than statistical inter-coder reliability.

Codes were subsequently organised into higher-order themes aligned with the PEPCII model components (physical and operational environment, pedagogical integration, ethical and cybersecurity considerations, cognitive and physical limitations, inclusive access and engagement, and instructional methods). This alignment served as an organising and validation logic rather than an a priori coding framework: themes were generated inductively and only then examined in relation to the PEPCII model components to identify confirmation or refinement needs.

Analytical saturation was considered achieved when additional transcripts yielded no substantively new codes or theme refinements. Representative quotations are reported in the Findings section to substantiate each analytical category and to demonstrate the empirical basis for validating and refining the PEPCII model.

The authors acknowledge their positionality as developers of the PEPCII model and as researchers involved in its empirical validation. While this positionality supported contextual sensitivity to model-related phenomena, it also required reflexive attention to potential confirmation bias. Accordingly, data analysis prioritised participants' experiential accounts prior to alignment with the PEPCII model components, and interpretations were critically examined through reflexive dialogue between authors and triangulation across stakeholder groups, consistent with design-based research principles emphasising transparency and contextual grounding in authentic educational settings (Baumgartner et al. 2003; Tinoca et al. 2022; Cochrane et al. 2023). Ethical procedures, informed consent, and data protection measures are described in the Declarations section.

Findings

To ensure transparency and auditability of the validation process, Table 5 synthesises key empirical findings by mapping them to the PEPCII model components (Table 3) and to the operationalised TRL levels guiding the validation logic (Table 2).

Table 5

Alignment of empirical findings with PEPCII components and TRL validation levels

Empirical finding (Results section)	Primary evidence sources	Aligned PEPCII component(s) (cf. Table 3)	TRL level (cf. Table 2)
Teachers' preparedness strongly influences the engagement of TPR-mediated students	Teacher focus groups (FG2); TPR-mediated student focus groups (FG1)	P – Pedagogical Integration; I – Instructional Methods	TRL 8 – validated through multi-stakeholder feedback in real-world use

Audio quality, background noise, and camera focus substantially increase cognitive load	TPR-mediated student focus groups (FG1); teacher focus groups (FG2)	C – Cognitive and Physical Limitations	TRL 7 – demonstrated during operational classroom implementation
Simultaneous control by multiple remote users leads to coordination problems	TPR-mediated student focus groups (FG1)	I – Instructional Methods; P – Physical, Operational and Educational Environment	TRL 7 – observed in authentic use conditions
TPR use is pedagogically suitable mainly for lectures and low-mobility learning activities	Teacher focus groups (FG2); in-class student written interviews	P – Pedagogical Integration	TRL 9 – stable and confirmed across courses and cohorts
Availability of real-time technical support reduces stress and increases participation confidence	TPR-mediated student focus groups (FG1); teacher focus groups (FG2)	C – Cognitive and Physical Limitations; I – Instructional Methods	TRL 8 – validated through repeated implementations
In-class students express uncertainty regarding privacy and camera visibility	In-class student written interviews	E – Ethical and Cybersecurity Considerations	TRL 8 – validated via stakeholder feedback
Visual presence of the TPR-mediated student (camera on and positioning)	Teacher focus groups (FG2); in-class student written interviews	I – Inclusive Access and Engagement	TRL 7 – demonstrated in classroom practice
Clear visual instructions and onboarding materials reduce cognitive strain	Teacher focus groups (FG2); TPR-mediated student focus groups (FG1)	I – Instructional Methods	TRL 9 – confirmed readiness for sustained use
Expectation management is essential for student well-being and motivation	TPR-mediated student focus groups (FG1); TPR-mediated student written interviews	I – Inclusive Access and Engagement; C – Cognitive and Physical Limitations	TRL 8 – validated post-course

Note. FG1 = TPR-mediated student focus groups; FG2 = teacher focus groups. Written interviews were conducted with TPR-mediated students and in-class students.

Factors that are influencing the adoption of the PEPCII model

The analysis revealed a set of interrelated factors influence the implementation and effective use of TPRs in higher education. These factors emerged consistently across teachers, TPR-mediated students, and in-class students and were grouped into six analytical categories: (1) technical functionality and usability, (2) pedagogical suitability, (3) user preparation and support needs, (4) experience and engagement, (5) social and ethical considerations, and (6) perceptions and attitudes. In the following text, we present the study's findings based on the previously described categories.

Technical functionality and usability:

Technical conditions strongly shaped the learning experience of TPR-mediated students and the instructional flow perceived by teachers. Both teachers and remote students highlighted the centrality of audio and video quality. Audio intelligibility depends on the speaker's distance and microphone pickup range, and ambient classroom noise, whispering and typing sounds reported as particularly disruptive. In larger halls, identifying a stable and meaningful viewing angle was challenging, and the use of whiteboard often resulted in camera focus problems. As one

TPR-mediated student noted, "*The robot camera couldn't keep focus when the teacher moved in front of the board… As a result, what the lecturer wrote was out of focus.*" (S10).

Mobility constraints further affected usability. Narrow passages, stairs, and physical obstacles sometimes required assistance from in-class peers to reposition the robot. Additionally, when several remote students shared a single TPR, difficulties arose due to simultaneous control attempts and the absence of agreed-upon control protocols. One participant described this situation as follows: "*Maybe that was it, that we all wanted to move it at the same time, and then, so to speak, whoever got there first got to move it, but I, for example, couldn't anymore.*" (S01).

A structured multi-user control and coordination protocol developed from the empirical findings is provided in Appendix 3, where the operational procedures and role structure for multi-user TPR participation are documented.

Pedagogical suitability:

Participants consistently differentiated between instructional situations in which TPR-mediated participation was perceived as appropriate and those in which it was not. Teachers and students agreed that lectures, seminars, and learning activities involving limited physical movement were generally well suited for TPR use. Among in-class students, 44/78 (56.4%) indicated they would consider participating via a TPR if physical attendance was not possible, while 27/78 (34.6%) reported they would do so in case of illness.

In contrast, both teachers and students considered TPR-mediated participation unsuitable for examinations and hands-on practical activities. TPR-mediated students also expressed reservations about highly interactive group work, where they felt at risk of marginalisation. One student explained: "*I don't know if it would be good in group work, because if there are like four people in the group present, then there are those robots, who maybe still kind of feel like they're left out.*" (S10).

User preparation and support needs:

Preparation and institutional support emerged as central enabling conditions for effective TPR use. Teachers emphasised the need for clear guidance on the robot's functionalities and limitations, including practical advice on classroom positioning and student involvement strategies. As one teacher stated, "*Information for the teacher: which spots in the classroom are suitable for the robot, how to involve the student.*" (T02).

Both teachers and students valued concise visual guidelines and onboarding materials. TPR-mediated students reported that brief introductory sessions, or alternatively instructional videos, were helpful in preparing them for participation robot-mediated students reported that a brief introductory session helped them prepare; if necessary, this could be replaced by an instructional video. Their learning experience was strongly influenced by the teachers' preparedness and willingness to actively involve remote participants. When several students share one TPR, participants suggested that predefined role distribution would reduce coordination problems.

Access to real-time technical support was repeatedly described as critical. A TPR-mediated student highlighted the reassurance this provided: "*The person who helped, so to speak, set up the robot gave me their phone number through the robot, said that if you have any problem, definitely call. That they're somewhere nearby in the building, and that, that did give a bit of a sense of security, that, that you know you're not alone with your issue*." (S04).

Experience and engagement:

Engagement levels varied markedly depending on instructional design and teacher behaviour. TPR-mediated students reported higher engagement when teachers had deliberately planned how the robot would participate in learning activities. In contrast, insufficient planning resulted in feelings of passivity and exclusion. One participant reflected: "*The teachers themself kind of maybe wasn't... they didn't always know what to do with us... and the whole lecture, the topic was also difficult... for us it was like even harder to understand anything at all...*" (S07).

These accounts indicate that teachers' conscious efforts to adapt instruction and interaction patterns were pivotal for creating meaningful learning experiences for TPR-mediated students.

Social and ethical considerations:

Within the in-class student group, 9/78 (11.5%) raised ethical concerns related to privacy and consent, particularly regarding what TPR-mediated students could see or potentially record. One student directly: "*What do the students on the other side of the screen see?*" (C02). In addition, in-class students observed that remote peers often became passive or invisible when not explicitly included in learning activities. As one participant noted, "*I wondered how natural the interaction felt for the remote student, how easily they could follow the lesson, and whether they felt included in group work or discussions.*" (C44).

Perceptions and attitudes:

Across stakeholder groups, TPRs were perceived as enabling more active participation than conventional videoconference-based hybrid learning, although they were not seen as a substitute for physical presence. TPR-mediated students emphasised the importance of managing expectations, noting that participation via a robot required sustained concentration and effort. One student described this tension as follows: *"...to be aware that this, this robot lecture, that on the one hand it is convenient. ...To still be prepared for the fact that it is not quite the same...you have to put in a lot of effort there, at least to listen as if for yourself, this concentration is sometimes even greater than in a lecture on the spot*." (S06).

Table 6 summarises the empirically identified factors influencing the adoption of TPRs in higher education and indicates which participant groups highlighted each factor.

Table 6
Empirically identified factors influencing the adoption of TPRs in higher education by participant groups

Categories	Factor	Teachers	In-class students	TPR-mediated students
Technical functionality and usability	Audio quality (mic pickup range, speaker distance)			✓
	Video quality (internet stability, camera focus)			✓
	Mobility limitations (stairs, obstacles)	✓	✓	✓
	Simultaneous control by multiple users			✓
Pedagogical suitability	Suitable for lectures/seminars with minimal movement	✓		
	Unsuitable for practical classes, exams	✓	✓	✓
	Willingness to participate via TPR		✓	
User preparation and support needs	Overview of TPR functionalities and operational limitations	✓	✓	✓
	Real-time technical support			✓
	Teacher preparedness and engagement			✓
	Clear division of control among multiple users			✓
Experience and engagement	Deliberate instructional planning by teachers			✓
	Passive feeling due to lack of active inclusion		✓	✓
Social and ethical considerations	Privacy and consent concerns		✓	
	Inclusion in social interactions		✓	
Perceptions and attitudes	Comparative advantage over videoconferencing	✓	✓	✓
	Expectation management	✓	✓	✓

Note. A "✓" indicates that the factor was explicitly mentioned by participants in the respective group during focus group interviews or written interviews. The table does not represent the frequency or relative importance of factors.

The PEPCII pedagogical design model improvements based on validation

Empirical validation in authentic synchronous hybrid learning contexts enabled a refinement to the PEPCII model by specifying how its existing components function under real instructional conditions. Rather than extending the model, the validation process sharpened each component by translating recurrent empirical patterns into concrete, context-sensitive design requirements that support participation, instructional coherence, and participant well-being.

Physical, Operational and Educational Environment (P)

Empirical basis (see Table 5; Table 6):

The classroom layout must be thought through. Identify spots from which, via the TPR's mediation, it is possible to see the teacher, the board, the screen and fellow students well. One teacher illustrated this by noting that "*...we had to arrange the groups in a way that the students in the robot could also take part in the circle, but overall there was nothing unpleasant or difficult — we just needed to think a little."* (T08).

To ensure a fluent learning process, both teachers and students emphasised the value of familiarising themselves with the possibilities and constraints of TPR use in advance, preferably in the actual learning environment. *"I do think that having five or six clear instructions on where and how to direct or move the assistant would be very helpful."* (T05). When such pre-class familiarisation is not feasible, participants suggested that a short interactive or instructional video can effectively support initial orientation and preparation for participation. In addition, the validation highlighted the importance of managing the acoustic and technical environment: background noise such as typing or whispering was reported to disrupt TPR-mediated participation, underscoring the need for quiet zones and stable, dedicated technical conditions for TPR use.

Ethical and Cybersecurity Considerations (E)

Empirical basis (see Table 5; Table 6):

Among in-class students, 9/78 (11.5%) expressed uncertainty regarding privacy, visibility, and consent in TPR-mediated settings, particularly when the functionality of the robot interface was not clearly understood. One student asked, "*How well can the fellow students hear and see what is actually going on in the class"* (C29).

Accordingly, the PEPCII model now foregrounds the need for explicit, shared explanations of TPR operation for all classroom participants. Beyond awareness, validation indicated the importance of clearly articulated behavioural expectations. The ethical and cybersecurity component was therefore refined to include the communication of agreed interactional and privacy guidelines, integrating ethical considerations directly into pedagogical design.

Pedagogical Integration (P)

Empirical basis (see Table 5; Table 6):

Across participant groups, teacher preparedness and uncertainty about how to pedagogically involve TPR-mediated students emerged as decisive factors shaping engagement and learning quality. One TPR-mediated student described situations in which „*…the teacher seemed completely overloaded… they didn't know how to divide their attention or what to do when a problem occurred.*“ (S06).

These findings informed a refinement of the Pedagogical Integration component, emphasising the provision of concrete examples, scenarios, and visual guidance illustrating pedagogically meaningful TPR use. Validation results further suggested that effective integration depends on experiential understanding. The model therefore highlights opportunities for teachers to gain hands-on experience with TPRs to design learning activities that align with the affordances and constraints of robot-mediated participation. As one teacher reflected, "*I went through the lesson in my thoughts, considering what I would need to change because there was now also someone participating via the robot, and how I could use the moments where I usually activate students also through the robot* (T08).

Cognitive and Physical Limitations (C)

Empirical basis (see Table 5; Table 6):

Participants across all groups described cognitive strain related to managing multiple interfaces, interpreting limited non-verbal cues, and responding to technical disruptions, alongside concerns about reduced confidence in the absence of immediate support.

In response, the Cognitive and Physical Limitations component was refined to foreground training, concise instructions, and prior practice as mechanisms for reducing cognitive load. TPR-mediated students emphasised the reassurance provided by direct access to technical support, noting that *"...the fear that it might just bump into a table… it would be good if we were shown how far it can move."* (S15). Teachers, in turn, highlighted the importance of verifying basic communicative functionality at the start of sessions and the challenges posed by reduced visual feedback, as one teacher observed: "*If there's no face, then it's tough – you can't tell whether they understand or whether they're participating."* (T10). These refinements explicitly link cognitive and physical considerations to sustained engagement and participant well-being.

Inclusive Access and Engagement (I)

Empirical basis (see Table 5; Table 6):

Findings indicated that inclusive participation in TPR-mediated learning depended on deliberate interactional practices. Reduced engagement was reported when remote students were visually or interactionally marginalised, as illustrated by one teacher's observation that *"…many students, I think, didn't notice at all… when a desk suddenly started talking."* (T10).

The PEPCII model was refined to emphasise proactive facilitation of movement, positioning, and information flow to support remote participation. Participants highlighted the absence of convenient channels for sharing links and materials, leading to the inclusion of supplementary text-based communication as a design consideration. One TPR-mediated student described the resulting workaround: "*We couldn't do the group work... one of us had to call by phone and the others wrote in Messenger, because otherwise there was an echo."* (S07). Validation further showed that in-class students' behaviour influences TPR-mediated experiences, motivating guidance addressing mutual responsibilities in hybrid interaction. Expectation management was also identified as a condition supporting inclusive participation and student well-being.

Instructional Methods (I)

Empirical basis (see Table 5; Table 6):

Teachers and TPR-mediated students consistently pointed to the need for practical, accessible instructional support and clearer expectation management regarding participation via TPRs. Participants emphasised the importance of having immediate guidance available in the event of technical disruptions, such as connection freezes or loss of control. As one TPR-mediated student noted, *"...perhaps it would help if, in situations where the window freezes or you get stuck, there were contacts immediately available for support — someone you could turn to…"* (S05).

Accordingly, the Instructional Methods component was refined to foreground structured preparation, including demonstration videos, FAQs, rehearsal opportunities, and brief technical checks at the beginning of sessions. One student reflected, "*It would be useful if there were examples, Q&A-style guidance about what to do in different situations. I just switched it off and on myself… a guide would have helped."* (S08). Clear communication of participation demands was identified as a condition supporting sustainable and effective TPR-mediated instruction.

Terminology across Table 5 and Table 6 and this refinement section was deliberately standardised to ensure analytical traceability between empirical findings and component-level design implications. This alignment enables transparent linking of recurrent empirical patterns to specific refinements of the PEPCII model, strengthening internal consistency and supporting interpretive clarity.

Discussion

This study examined the factors that influence the effective use of TPRs in higher education and empirically validated the PEPCII model in authentic synchronous hybrid learning contexts. Rather than reiterating the findings, this discussion synthesises cross-cutting patterns across stakeholder perspectives to clarify their pedagogical significance and to establish a rationale for refining the PEPCII model in relation to prior research on technology integration and hybrid learning (Mishra and Koehler 2006; Raes et al. 2020; Wood et al. 2025).

Pedagogical readiness and teacher agency in TPR-mediated learning

Across participant groups, teacher preparedness emerged as a decisive factor shaping the quality of TPR-mediated learning. This finding is consistent with prior research showing that the educational impact of digital technologies depends less on availability than on teachers' capacity to integrate them pedagogically (Mishra and Koehler 2006; Voogt et al. 2013; Dinçer 2024). While the TPACK framework emphasises the integration of technological, pedagogical, and content knowledge (Mishra and Koehler 2006), empirical studies have demonstrated persistent challenges in operationalising this integration in complex instructional settings (Raes et al. 2020; Gamberini et al. 2022).

The present findings show that these challenges are amplified in synchronous hybrid environments involving TPRs. Teachers who deliberately planned for the visibility, interaction, and participation of TPR-mediated students enabled higher engagement and stronger inclusion, aligning with earlier findings on the importance of structured instructional design in hybrid learning (Müller et al. 2023; Wood et al. 2025). Conversely, insufficient preparation frequently reduced remote students to passive observers, despite the affordances of physical telepresence.

These patterns indicate that teacher agency in TPR-mediated settings lies less in technology use per se than in the orchestration of learning setup that involves both social and technological elements and classroom dynamics. Similar to earlier technology-integration research, TPRs did not compensate for weak instructional design but amplified existing pedagogical practices (Mishra and Koehler 2006; Voogt et al. 2013), underscoring the need for design-oriented frameworks that translate pedagogical intent into actionable hybrid learning practices.

Technical constraints, cognitive load, and usability

Technical issues related to audio quality, visual stability, mobility, and multi-user control were consistently reported as shaping the learning experience of TPR-mediated students. Comparable constraints have been documented in earlier studies on TPRs and synchronous hybrid learning (Weibel et al. 2023; Elmimouni et al. 2023; Leoste et al. 2024). Crucially, the present findings demonstrate that these challenges manifest primarily as increased cognitive load rather than as isolated technical inconveniences.

In line with Cognitive Load Theory (Sweller 1988), continuous attentional compensation reduced students' capacity to engage with instructional content. While technology acceptance models emphasise perceived ease of use as a determinant of adoption (Davis 1989; Venkatesh et al. 2003), the present findings extend this perspective by showing that usability directly affects instructional quality and students engagement in practice (Scherer et al. 2019). Participants also identified design-level mitigations, such as prior familiarisation, clear control protocols, and real-time technical support, echoing earlier research that highlights the role of pedagogical and organisational scaffolding in reducing cognitive strain (Parasuraman 2000; Baumgartner et al. 2003).

Inclusion, presence, and ethical visibility

The embodied and socially visible nature of TPRs introduced distinct inclusion-related and ethical challenges that extend beyond those associated with conventional videoconferencing. Prior research has shown that TPRs can enhance social presence and engagement compared to screen-based participation (Leoste et al. 2022; Häfner et al. 2023; Hu et al. 2024), yet these benefits depend on deliberate pedagogical structuring (Fabian et al. 2024; Asadi and Fischer 2025).

Visibility, of both the TPR-mediated student and the classroom environment, proved central to participation and perceived legitimacy, consistent with Community of Inquiry and social presence research (Short et al. 1976; Garrison et al. 1999). Ethical concerns related to privacy, consent, and the observational capabilities of TPRs were particularly salient for in-class students. Similar concerns have been raised in earlier studies on telepresence and accessibility, which stress the need for transparent ethical guidelines and shared norms (Floridi et al. 2018; Weibel et al. 2023; CAST 2024). These findings reinforce arguments from Universal Design for Learning and digital ethics literature that inclusion and ethical clarity are integral to pedagogical design rather than peripheral considerations (Floridi et al. 2018; CAST 2024).

Implications for pedagogical design

Taken together, the findings indicate that the effectiveness of TPR-mediated hybrid learning depends less on technological novelty than on coherent pedagogical integration, consistent with broader research on hybrid and blended learning (Raes et al. 2020; Yu et al. 2022; Liu et al. 2024). Technical and cognitive constraints become pedagogically consequential when they are not anticipated through design, while inclusion and ethical visibility must be actively constructed rather than assumed.

These interrelated dynamics highlight the need for a structured pedagogical design model capable of operationalising pedagogical, technical, cognitive, and ethical dimensions in practice. Accordingly, the following section details how these empirical insights informed targeted refinements of the PEPCII model, strengthening its capacity to guide implementation and support educational quality and participant well-being in TPR-mediated higher education.

Refinement of the PEPCII Model

The empirical validation conducted in this study enabled a targeted refinement of the PEPCII pedagogical design model based on sustained implementation in authentic synchronous hybrid learning contexts. While the original model was conceptually grounded in prior literature, validation data revealed how its components operated in practice and where greater operational specificity was required. Table 7 summarises this refinement by contrasting the conceptual and empirically validated versions of each PEPCII component and linking each adjustment to the empirical triggers identified in Table 6.

Table 7
PEPCII model refinements informed by empirical validation.

PEPCII component	Before validation	After validation	Empirical trigger (Table 5)
P – Physical, Operational and Educational Environment	General infrastructure readiness and classroom suitability for TPR use	Activity-specific spatial design, robot positioning, movement paths, audio zoning, and mandatory pre-class environmental testing	Audio quality; background noise; camera focus stability; classroom layout
E – Ethical and Cybersecurity Considerations	Ethics and cybersecurity addressed as general principles and compliance issues	Explicit interaction-level protocols for consent, camera visibility, observation boundaries, and shared responsibility	Privacy concerns; consent ambiguity; camera visibility
P – Pedagogical Integration	Alignment of TPR use with learning outcomes and teaching strategies	Deliberate interaction design: structured turn-taking, role assignment, and explicit inclusion of TPR-mediated students	Teacher preparedness; variability in student engagement
C – Cognitive and Physical Limitations	User-related cognitive and physical constraints inherent to TPR technology	Design-sensitive cognitive load management through task sequencing, simplified interfaces, and predefined control protocols	Cognitive load; multitasking; multi-user control
I – Inclusive Access and Engagement	Telepresence assumed to provide access and inclusion	Clear distinction between access and inclusion; proactive strategies for visibility, acknowledgement, and participation	Social presence; asymmetry in participation
I – Instructional Methods	Broad instructional guidance without differentiation by experience level	Stage-specific methods (introductory, iterative, advanced) and emphasis on rehearsal and continuous professional development	Training needs; rehearsal effects

Rationale for refinement

The model refinement was guided by multi-stakeholder empirical evidence from teachers, TPR-mediated students, and in-class students. Rather than extending the model conceptually, the refinement focused on clarifying and operationalising its existing components in line with design-oriented research that emphasises empirical validation through implementation (Mankins 2009; Cobos et al. 2021). Each refinement responds directly to recurrent empirical triggers, ensuring transparent traceability between findings and model development (Table 7).

Summary of component-level refinements

Across components, the refinement process consistently shifted emphasis from general principles toward actionable design guidance. The Physical, Operational and Educational Environment component was refined to distinguish baseline infrastructure readiness from activity-specific spatial design, including robot positioning, audio zoning, and pre-class environmental testing. Ethical and Cybersecurity Considerations were reframed from compliance-oriented principles to interaction-level protocols addressing privacy concerns, consent ambiguity, and camera visibility, aligning ethics with everyday classroom practices (Weibel et al. 2023).

For Pedagogical Integration, empirical evidence demonstrated that teacher preparedness and engagement variability were decisive for participation, leading to a refinement that foregrounds deliberate interaction design and explicit inclusion of TPR-mediated students. Cognitive and Physical Limitations were reframed as design-sensitive variables rather than fixed user constraints, with cognitive load, multitasking, and multi-user control addressed through task sequencing and predefined control protocols. Inclusive Access and Engagement was refined to clearly distinguish access from inclusion, emphasising proactive strategies to address participation asymmetry and social presence. Finally, Instructional Methods were specified by implementation stage, highlighting training needs, rehearsal effects, and ongoing professional development as prerequisites for sustainable TPR integration.

Validated model status and transferability

Together, these refinements strengthen the PEPCII model as an operationally grounded pedagogical design framework. Each component is now explicitly grounded in empirical triggers and translated into concise design guidance, consistent with TRL-based validation of educational models through real-world use (Kasuk et al. 2025c). While the refinement was conducted in higher-education contexts with relatively high digital readiness, the underlying design principles are transferable to other synchronous hybrid settings, subject to institutional support and participant digital literacy.

Conclusion

This study examined the factors influencing the effective use of TPRs in higher education and empirically validated the PEPCII model in use within authentic synchronous hybrid learning contexts. Drawing on multi-stakeholder data from teachers, TPR-mediated students, and in-class students, the findings indicate that the educational value of TPRs depends less on technological availability than on pedagogical integration, instructional preparation, and institutional support structures.

The results show that TPR-mediated participation can support social presence, engagement, and access when physical attendance is constrained, while also revealing persistent challenges related to technical reliability, cognitive load, coordination in multi-user scenarios, and ethical visibility. These challenges are not isolated technical issues but are closely intertwined with pedagogical decisions and classroom practices, underscoring that TPRs function as learning setups involving both social and technological elements rather than as neutral instructional tools.

By examining the PEPCII model through sustained real-world use, this study contributes to existing technology integration frameworks by operationalising pedagogical, technical, cognitive, ethical, and inclusion-related considerations within a single design-oriented model. While frameworks such as TPACK articulate the knowledge domains required for technology integration, the PEPCII model provides structured guidance for enacting this knowledge in embodied and synchronous hybrid learning environments involving TPRs.

Empirical validation enabled a targeted refinement of the PEPCII model by specifying concrete design considerations, including activity-specific spatial planning, explicit consent and visibility protocols, proactive inclusion strategies, and systematic approaches to cognitive load management. These refinements strengthen the model's internal coherence and practical usability, positioning the PEPCII model as a pedagogical design framework whose readiness for practical use has been examined in higher education contexts.

Several limitations should be acknowledged. First, the study relied predominantly on self-reported qualitative data from focus groups and written reflections, without incorporating observational measures or objective indicators of learning outcomes. Therefore, conclusions relate to perceived usability and pedagogical coherence rather than demonstrable instructional effectiveness Second, although the PEPCII model reached TRL 9 within the investigated contexts in this study, validation was conducted in digitally mature higher education institutions and has not yet been independently replicated across diverse institutional or national settings. Third, participation rates varied across stakeholder groups, particularly among in-class students, which may introduce response bias and limit representativeness. Fourth, the authors' dual role as developers and evaluators of the PEPCII model may entail interpretive bias despite the application of reflexive analytical procedures. Fifth, findings are partially shaped by the specific technological affordances of the TEMI platform, and transferability to other telepresence systems should therefore be approached with caution. Finally, while the study adopted a design-based research orientation, it did not involve multiple iterative redesign cycles within the same instructional context.

As future research, the functioning of the PEPCII model should be tested at different levels of education and in different countries where students' and teachers' digital competences and the digital readiness of infrastructure differ from those of the present study. In addition, the longer-term effects of TPR-mediated participation on well-being, teaching, and learning, including learning outcomes and school organizational culture, should be examined. Further studies should include mixed methods that enable the integration of qualitative insights from observations and quantitative outcome-based indicators, which would help to understand the effectiveness of teaching and learning. Comparative studies between different TPR models would help to understand how different platforms influence the PEPCII model. Additionally, it could be examined how new developments, such as AI, could reduce cognitive load and increase inclusivity through supported navigation, automated title generation, and adaptive interaction protocols.

Taken together, the findings of this study indicate that TPRs can enhance participation and presence in synchronous hybrid learning when their integration is guided by a coherent pedagogical design logic. The refined the PEPCII model advances existing technology integration approaches by explicitly addressing environmental, cognitive, ethical, and instructional dimensions that become critical in robot-mediated learning. In doing so, the model moves the use of TPRs beyond ad hoc experimentation toward more systematic, inclusive, and pedagogically grounded hybrid learning practices.

Declarations

Ethical Approval Statement

Ethical review and formal approval were not required for this study ("Validation of the PEPCII Pedagogical Design Model via Telepresence Robot Use in Higher Education"), in accordance with applicable institutional guidelines and national legislation, and in line with the Estonian Code of Conduct for Research Integrity. The study was conducted in an educational context involving voluntary adult participants and did not include the collection of sensitive or personally identifiable data. This exemption from formal ethical review was confirmed at the institutional level by the Director of the IT College, Tallinn University of Technology. All procedures performed in this study were in accordance with established ethical standards for research involving human participants and complied with the General Data Protection Regulation (EU) 2016/679.

Informed Consent

Informed consent was obtained from all participants included in the study. Participation was voluntary, and participants were informed about the purpose of the study, the nature of their involvement, their right to withdraw at any time without consequences, and the use of anonymised data for research and publication purposes.

For focus group interviews, informed consent was obtained verbally prior to the start of audio recording. Participants were informed about recording procedures, data processing, and confidentiality measures, and recording commenced only after consent was obtained.

For written responses collected via online questionnaires, participants were provided with an introductory explanation of the study and data handling procedures. Submission of the questionnaire was considered as informed consent.

All data were anonymised during transcription, and no identifying information was retained. Data were stored securely and accessed only by the research team.

Data availability statement

The anonymised qualitative data and analytical materials supporting the findings of this study are publicly available in the Zenodo repository (https://doi.org/10.5281/zenodo.18982861) under Creative Commons Attribution 4.0 International. The repository contains anonymised focus group interview transcripts from teachers and TPR-mediated students, anonymised written interview responses from TPR-mediated and in-class students, and the processed dataset used in the qualitative thematic analysis. It also includes the qualitative coding framework and codebook defining the PEPCII analytical dimensions, together with documentation describing the data preparation and coding procedures. All materials were fully anonymised in accordance with institutional ethical guidelines and applicable data protection regulations.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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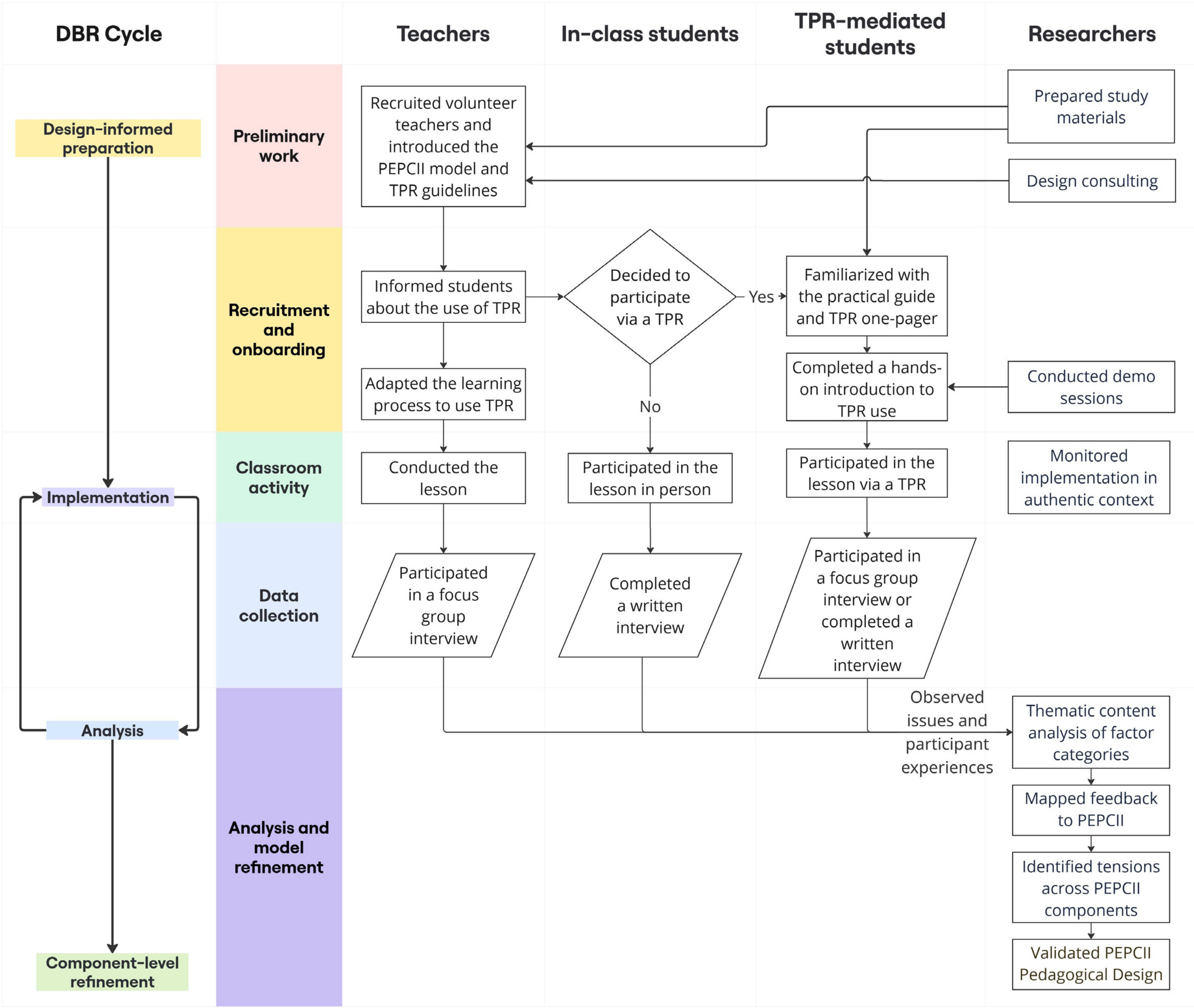

DBR Cycle
Teachers
In-class students
TPR-mediated students
Researchers
Design-informed preparation
Preliminary work
Recruited volunteer teachers and introduced the PEPCII model and TPR guidelines
Prepared study materials
Design consulting
Recruitment and onboarding
Informed students about the use of TPR
Decided to participate via a TPR
Yes
No
Familiarized with the practical guide and TPR one-pager
Adapted the learning process to use TPR
Completed a hands-on introduction to TPR use
Conducted demo sessions
Implementation
Classroom activity
Conducted the lesson
Participated in the lesson in person
Participated in the lesson via a TPR
Monitored implementation in authentic context
Data collection
Participated in a focus group interview
Completed a written interview
Participated in a focus group interview or completed a written interview
Analysis
Analysis and model refinement
Observed issues and participant experiences
Thematic content analysis of factor categories
Mapped feedback to PEPCII
Identified tensions across PEPCII components
Validated PEPCII Pedagogical Design
Component-level refinement

Curriculum vitae

Personal data

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2012-2021	Tallinn University of Technology, Office of Academic Affairs, Educational Technology Centre, Multimedia Specialist-Education Technology Officer
2017-2018	Tallinn University of Technology, Office of Academic Affairs, Educational Technology Centre, Head of Centre
2011-2012	Kehtna Economy and Technology School, Head Teacher of ICT
2002-2011	Kehtna Economy and Technology School, ICT teacher

Field of research

- **ETIS RESEARCH FIELD 2. Culture and Society; 2.10. Education**
- **CERCS RESEARCH FIELD S281 Computer-assisted education**

Scientific work

1. Kasuk, Tiina; Leoste, Janika; Rakic, Slavko; Banko, Aalo (2026). Enhancing synchronous hybrid learning with telepresence robots: a PEPCII pedagogical design model for remote and onsite student engagement. Robotics in Education: Proceedings of the RiE 2025 Conference: 16th International Conference on Robotics in Education (RiE2025) (in press)
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Teadustöö põhisuunad

- ETIS VALDKOND 2. Ühiskonnateadused ja kultuur; 2.10. Kasvatusteadused
- CERCS VALDKOND S281 Arvuti õpiprogrammide kasutamise metoodika ja pedagoogika

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