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RECEIVED 30 May 2025

ACCEPTED 27 August 2025

PUBLISHED 17 September 2025

CITATION

Fröhlich L, Görlach J, Thormählen T and
Mahnken AH (2025) Immersive virtual reality
training in radiology: impact on motivation,
interest, engagement, and learning outcomes.
Front. Educ. 10:1638410.
doi: 10.3389/feduc.2025.1638410

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Immersive virtual reality training in radiology: impact on motivation, interest, engagement, and learning outcomes

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Background: Immersive virtual reality (IVR) is becoming increasingly important in medical education. In radiology, IVR as a tool for practicing image interpretation and diagnosis of pathologies has rarely been subject of research to date. This exploratory study investigated a self-programmed IVR application and its potential to improve radiology education for medical students.

Methods: An IVR learning environment was programmed which enables users to view 3D models of real patients and interact with them using various tools. Fourth- to sixth-year medical students ($n = 26$) participated in a 1 h IVR training session in small groups between November 2022 and January 2023. Subsequently, they completed an anonymous online survey comprising 37 items. Data were analyzed, with correlations examined using Spearman's non-parametric rank correlation.

Results: The IVR training increased students' motivation ($M = 3.6$) and interest in radiology ($M = 3.2$) and fostered enjoyment ($M = 3.7$) as well as a more active ($M = 3.6$) and intensive ($M = 3.3$) engagement. IVR was considered a helpful tool to enhance the practical relevance of radiology education, to improve the immediate cognitive and psychomotor learning outcomes related to anatomy and radiology, such as interpreting cross-sectional images ($M = 3.5$) and identifying anatomical structures ($M = 3.6$) as well as pathological changes ($M = 3.3$) and to promote skill development ($M = 3.2$), learning transfer ($M = 3.2$) and long-term knowledge retention ($M = 3.3$). The usability, design, tools and didactic functions of the IVR application are strongly associated with learning process- and learning outcome-related variables.

Conclusion: IVR-based learning is a promising addition to traditional radiology education to enhance motivation, interest and learning. However, the success of IVR depends on its design, usability and integration into the curriculum. The study highlights the need for further research on the added value of IVR across the educational sector.

KEYWORDS

radiology, immersive virtual reality, motivation, interest, learning outcomes

Introduction

Medical imaging is crucial for diagnosis, treatment planning and follow-up care across the healthcare system. Not only in radiology but also in many other disciplines, the interpretation of radiological images is integral to daily medical practice. Additionally, image-guided, minimally invasive therapies are increasingly important for patient care. Hence, even non-radiologists need a general knowledge of imaging modalities and basic image interpretation skills (Bork et al., 2019; Dmytriw et al., 2015; Zwaan et al., 2017). Radiological image interpretation requires knowledge of anatomical structures and radiological anatomy. Medical students, particularly those with poor mental rotation skills and spatial abilities, often struggle with transferring 2D to 3D anatomy and identifying anatomical structures in different imaging modalities, especially cross-sectional images (CT and MRI scans) (Bork et al., 2019). Research indicates that students feel underprepared in basic image interpretation, highlighting the need for improved radiology education (Dmytriw et al., 2015; Heptonstall et al., 2016). To better prepare students for future medical practice, the integration of radiology and anatomy education (Bork et al., 2019; Heptonstall et al., 2016) and innovative teaching concepts, such as technology-enhanced approaches like immersive learning environments, are necessary to promote students' motivation, interest and positive achievement emotions. Beyond cognitive skills, these affective factors are crucial for academic success and thus play an important role in ensuring a highly skilled workforce and excellent patient care. Intrinsic or autonomous motivation (self-determination theory; SDT) (Deci and Ryan, 2009), situational and individual interest (theory of interest development) (Hidi and Renninger, 2006) and positive achievement emotions like enjoyment (Control Value Theory of Achievement Emotions; CVTAE) (Pekrun, 2006; Plass and Kaplan, 2016) contribute to deeper learning, greater attention and engagement, a positive self-concept of ability, higher learning effort and higher academic achievement (Gorges et al., 2024; Hidi and Renninger, 2006; Kusrkar et al., 2011; Pekrun et al., 2011). These affective characteristics can be promoted through targeted, subject-specific pedagogical interventions (Gorges et al., 2024; Hidi and Renninger, 2006; Kusrkar et al., 2011; Plass and Kaplan, 2016). Constructivism as an important learning theory further emphasizes the relevance of fostering motivation, interest and active acquisition of knowledge and skills by creating interactive and learner-centered learning environments that facilitate experiential and situated learning. Learning is viewed as an active, constructive process. Accordingly, learning environments should be authentic, enable active participation and social interaction and allow learners to acquire knowledge in contexts that reflect future practice (Arnold and Kempkes, 1998).

Immersive Virtual Reality (IVR)-based learning has the potential to meet these requirements. Compared to other teaching methods, IVR has some unique features: immersion, presence and interactivity. Unlike non-immersive VR displayed on screens (e.g., desktop or smartphone), IVR uses head-mounted displays (HMD) to fully immerse users in virtual worlds, enabling contextualized experiences that support hands-on practice and repetitive skill acquisition with tasks that would

be impossible in the real world (Dalgarno and Lee, 2010; Hamilton et al., 2021). By linking theory and practice, IVR fosters problem-based and experiential learning, creating a fully learner-centered approach consistent with constructivist principles (Fromm et al., 2021). Hence, IVR is a promising tool for practical education to gain knowledge and skills. As a result, IVR is increasingly used in education, especially medical education (Dalgarno and Lee, 2010; Makransky et al., 2019a).

In medical education, IVR training has already proven to be a promising tool (Barteit et al., 2021). Its immersive, interactive nature allows creating clinic-based experiences, opportunities to interact with clinically relevant material in realistic settings, apply knowledge in practice-oriented scenarios and repeat procedures safely in ways not possible with traditional methods (Pottle, 2019). Thus, IVR has already been successfully used for various medical training scenarios, including anamnesis, planning and performing medical interventions and emergency simulations. It has been used not only for teaching students but also for the training of physicians. IVR-based learning is mainly utilized in surgery (Barteit et al., 2021). Studies show that IVR improves performance for various surgical procedures by leading to faster operations with better overall outcomes, a lower error rate and fewer injuries (Mao et al., 2021; Pottle, 2019).

In anatomy education, research confirms that IVR improves students' anatomy knowledge and performance by providing a 3D view of the body, virtual dissection and recreation of anatomical structures (Sinha et al., 2022). Moreover, initial studies investigating Augmented Reality (AR) applications (virtual objects overlay the real world) integrating 3D anatomy models with corresponding radiological images (X-rays, cross-sectional images) show that knowledge of radiological anatomy also enhances understanding of normal anatomy, anatomical spatial relations and spatial reasoning skills (Bork et al., 2019).

In radiology, research has largely focused on AR for planning and training image-guided interventions. Studies examining IVR in radiology education as a tool for practicing diagnosis skills and its impact on motivation, interest and learning outcomes are scarce (Lang et al., 2024). A rare exception is a study by Wu et al. (2022) ($n = 18$) showing that IVR teaching sessions including different case diagnoses and quizzes can be a useful learning tool for radiology. However, aspects such as motivation or interest are not considered in this study.

Overall, empirical research indicates several positive effects of IVR. It supports the acquisition of declarative and procedural knowledge as well as cognitive, psychomotor and affective skills (Hamilton et al., 2021), often outperforming traditional or non-immersive methods in immediate and long-term learning outcomes (Di Natale et al., 2020; Makransky and Mayer, 2022; Wu et al., 2020). Initial positive results have also been found on learning transfer (Makransky et al., 2021; Wu et al., 2020). Additionally, IVR-based learning increases motivation, interest, enjoyment, engagement, self-efficacy and learning persistence (Jensen and Konradsen, 2018; Makransky et al., 2019a; Makransky and Lilleholt, 2018; Parong and Mayer, 2018). Despite these promising results, empirical findings regarding the impact of IVR in education are not consistent. Some empirical works show no effects (Di Natale et al., 2020; Hamilton et al., 2021) or even negative effects of IVR on learning (Makransky et al., 2019b; Parong and Mayer, 2018), highlighting the need for further research.

To address these research gaps, the present study developed and evaluated an IVR learning environment to investigate its didactic

Abbreviations: CTML, cognitive theory of multimedia learning; CVTAE, control value theory of achievement emotions; IVR, immersive virtual reality.

potential and its possible contributions to improving radiology education for medical students. The aim of this exploratory study was to examine students' perceptions of the self-programmed IVR application, including usability, design and interactive features. The study also explored potential effects on students' motivation, interest, enjoyment, engagement, learning experiences and perceived learning outcomes. The study also investigated whether design and didactic elements of the IVR application were associated with affective and learning-related characteristics.

Materials and methods

An IVR learning environment for HMD was programmed. Based on anonymized 2D CT data sets (DICOM images), patient-specific interactive volume renderings were generated using a custom shader inside the 3D development platform Unity Engine, version 2021.2.0f1 (Unity Technologies, San Francisco, California). A system equipped with an NVIDIA GeForce RTX 2080 Super GPU was used, with a minimum frame rate of 60 frames per second (fps). The IVR application enables users to view and interact with the 3D visualizations of real patient's data (Figure 1) using various tools like 360-degree view, structure marking, cutting and transparency adjustments (windowing). Didactic features were also integrated, including live streaming via a projector for group teaching and video recording for learning outcome assurance. In this study, HTC Vive HMDs and HTC Vive controllers (HTC Corp, Taoyuan, Taiwan) were used.

Study design and data collection

User testing was conducted with a sample consisting of 4th-, 5th-, and 6th-year medical students ($n = 26$), who had already participated in radiology courses. Participants were recruited via e-mail in October 2022 and randomly assigned to eight focus groups. All students took part in the survey voluntarily and informed consent to participate was obtained from all participants.

IVR training took place extracurricularly from November 2022 to January 2023, with each session lasting about an hour. The IVR training session began with a short introduction to the teaching concept and a brief technical training. Students then tested the IVR application by performing different tasks under guidance, with opportunities for active experimentation and discussion throughout the session. The IVR training focused on 3D models of the thorax and abdomen. The following tasks were included:

- 1 Navigating through anatomical structures in 3D models of thorax and abdomen.
- 2 Identifying key anatomical landmarks and organs.
- 3 Exploring topographic anatomy by rotating, slicing and zooming into 3D models.
- 4 Interpreting cross-sectional images to link anatomy with radiological imaging.

At the end of the test session, the students completed an anonymous online survey (Supplementary Table 1) to assess the concept, the IVR learning environment and their perceptions on its impact on motivation, interest, enjoyment and learning. The survey consisted of 37 items addressing demographics, prior IVR experience, usability and design of the IVR application as well as motion sickness. It also covered the contribution of the IVR training to motivation, interest, enjoyment, engagement, learning process, perceived cognitive and psychomotor learning outcomes related to anatomy and radiology and potential benefits for learning transfer and long-term retention. Responses were recorded on a four-point Likert scale (1 = "strongly disagree" to 4 = "strongly agree"). Data were collected using REDCap, version 13.2.4 (Vanderbilt University, Nashville, Tennessee).

Statistical analysis

Statistical analysis was performed using SPSS, version 29 (IBM, Armonk, New York, NY, USA). Descriptive analyses were conducted for all items. Scales were generated for correlation analyses (response specifications, scoring rules and codification key; see

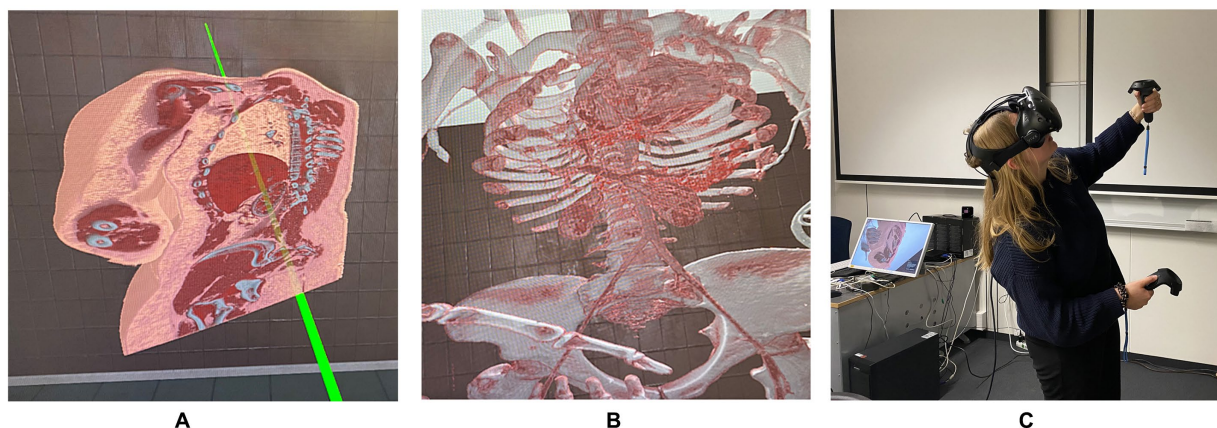


FIGURE 1

Screenshots of exemplary 3D models with different colour scales and virtual lighting. (A) illustrates soft tissue, (B) shows a dataset optimized for bone representation, (C) shows a medical student training with the IVR application including the 3D models seen in (A) and (B).

Supplementary Table 1). A principal component analysis (PCA) with varimax rotation was performed to test whether the variables can be combined into one scale. The suitability of the data for PCA was assessed using the KMO test (acceptable when ≥ 0.50). Factor extraction was guided by the Kaiser criterion along with the scree plot, with acceptable factor loadings set at > 0.30 and high at ≥ 0.50 . All variables achieved factor loadings > 0.65 . Reliability analyses were performed to assess the internal consistency of the scales using Cronbach's α (acceptable when $\alpha > 0.70$) (**Table 1**). Variables with discriminatory power < 0.30 were discarded. The reliability of scales consisting of only two items was measured using the Spearman-Brown coefficient (r_{sb}). According to [Hair et al. \(2019\)](#), values above 0.60 and up to 0.70 are acceptable in exploratory studies and for scales with a small number of indicators. Reliability values tend to be lower for short scales, but this does not mean bias. Thus, acceptable reliability values were set at $r_{sb} > 0.60$, with all values reaching $r_{sb} \geq 0.67$ (**Table 1**). For bivariate correlation analyses, Spearman's nonparametric rank correlation (Spearman's rho) was used due to the ordinal scaled variables. A p -value of ≤ 0.05 was considered to be statistically significant. Cohen's measure of effect size was used to assess the strength of relations ($r \geq 0.10$ = small, $r \geq 0.30$ = medium, $r \geq 0.50$ = large association).

Results

Descriptive results

All students who participated in the IVR training session completed the online survey ($n = 26$). The sample consisted of 46% female ($n = 12$) and 54% male ($n = 14$) participants with a mean age

of 25.7 years ($SD = 3.98$). Most participants were 5th year students ($n = 12$; 48%), followed by 4th ($n = 9$; 36%) and 6th year students ($n = 4$; 16%). About two-thirds of the participants ($n = 17$; 65%) had no previous experience with IVR.

The majority of students rated the handling and usability of the IVR positively. No participant was affected by motion sickness (e.g., dizziness or nausea). The various tools regarding the interaction with the 3D visualizations ($M = 3.3$) as well as the didactic functions, i.e., live stream of the IVR application via a projector ($M = 3.5$) and video recording to save learning outcomes ($M = 2.7$), were evaluated as useful and helpful.

The students reported that the IVR training increased their learning motivation ($M = 3.6$) and interest in radiology ($M = 3.2$). Moreover, the IVR training fostered positive emotions and engagement. The students stated that they enjoyed learning with the IVR application ($M = 3.7$) and the IVR training supports them to engage more actively ($M = 3.6$) as well as more intensively ($M = 3.3$) with the learning content.

When asked about the cognitive and psychomotor learning objectives, the IVR application was rated as a helpful tool to increase anatomical understanding using sliceable data sets ($M = 3.7$), to improve understanding of topographic anatomy ($M = 3.8$), to better identify anatomical structures ($M = 3.6$) and pathological changes ($M = 3.3$) and to better learn how to interpret cross-sectional images (CT and MRI) ($M = 3.5$). Furthermore, students assumed that the hands-on IVR training promotes long-term learning effect ($M = 3.3$), improves skill development ($M = 3.2$) and facilitates the application of acquired knowledge to practice (learning transfer) ($M = 3.2$). In addition, it was reported that IVR-based learning is very instructive ($M = 3.2$), IVR training meaningfully supported the learning process complementary to traditional learning methods ($M = 3.3$), increases the practical relevance of previous traditional radiology education ($M = 3.2$) and better visualizes radiology learning content ($M = 3.4$). Students concluded that the IVR application is a useful addition to previous traditional radiology teaching ($M = 3.5$) and thus, the use of IVR is an overall improvement in radiology education ($M = 3.6$).

Correlation analyses

In the correlation analyses (**Supplementary Table 2**), a significant correlation was found between the usability of the IVR application and learning engagement ($r = 0.43$, $p = 0.03$) and learning transfer ($r = 0.46$, $p = 0.02$). The design of the IVR application also correlated significantly with engagement ($r = 0.55$, $p = 0.004$) and learning transfer ($r = 0.53$, $p = 0.007$) and, in addition, with the improvement of both learning process ($r = 0.55$, $p = 0.004$) and skill development ($r = 0.54$, $p = 0.005$). The usefulness of the different tools for interacting with the 3D visualization was also related significantly to engagement ($r = 0.57$, $p = 0.003$), learning transfer ($r = 0.42$, $p = 0.04$) and improvement of the learning process ($r = 0.53$, $p = 0.005$), but additionally correlated significantly with interest ($r = 0.51$, $p = 0.008$), long-term learning effect ($r = 0.54$, $p = 0.005$) and improvement of radiology teaching ($r = 0.45$, $p = 0.03$). The mentioned didactic functions of the IVR application also had a great effect on items and scales related to motivation, interest and learning. The didactic functions correlated strongly with motivation ($r = 0.52$, $p = 0.007$), interest ($r = 0.54$, $p = 0.004$), engagement ($r = 0.63$, $p = 0.001$),

TABLE 1 Internal consistency (Cronbach's alpha), mean and standard deviation for each measurement instrument.

Item/scale	N = 26		
	α	r_{sb}	M (SD)
Usability	0.79		3.34 (0.51)
IVR design	— ^a		2.46 (0.51)
IVR tools	— ^a		3.31 (0.47)
Didactic functions		0.69	3.13 (0.63)
Motivation	— ^a		3.58 (0.64)
Interest	— ^a		3.27 (0.83)
Enjoyment	— ^a		3.73 (0.45)
Improvement of learning process	0.86		3.29 (0.56)
Engagement		0.67	3.46 (0.52)
Learning transfer	— ^a		3.20 (0.71)
Long-term learning effect	— ^a		3.32 (0.75)
Skill development	— ^a		3.24 (0.66)
Cognitive and psychomotor learning outcomes	0.84		3.55 (0.42)
Improvement of radiology teaching		0.82	3.54 (0.54)

α , Cronbach's alpha; r_{sb} , reliability values of Spearman-Brown coefficient; M, mean; SD, standard deviation.

^aSingle-item indicator.

improvement of the learning process ($r = 0.66$, $p < 0.001$), learning transfer ($r = 0.59$, $p = 0.002$), long-term learning effect ($r = 0.49$, $p = 0.01$), skill development ($r = 0.57$, $p = 0.003$), achievement of the cognitive and psychomotor learning outcomes ($r = 0.46$, $p = 0.02$) and improvement of radiology teaching ($r = 0.61$, $p = 0.001$).

Discussion

In recent years, IVR has been increasingly implemented in medical education, driven by its potential to advance teaching practices and improve educational outcomes. This trend creates a strong need for close evaluation of the conditions under which IVR can effectively support learning.

Previous studies show that compared to non-immersive VR, such as desktop VR, the use of IVR offers didactic advantages in medical training that are particularly relevant in radiology. IVR achieves better results in teaching abstract content and procedural skills than non-immersive methods (Di Natale et al., 2020; Hamilton et al., 2021). IVR enables a high degree of spatial immersion and intuitive interaction with 3D image data. This can be particularly beneficial for the understanding of complex anatomical structures, developing mental 3D models and improving spatial thinking, which skills play a central role in image interpretation and diagnosis in radiology (Sinha et al., 2022). In addition to the potential cognitive benefits, studies show that learners prefer IVR to non-immersive methods due to higher levels of presence and interest. Furthermore, IVR achieves higher scores on important non-cognitive outcomes such as motivation, engagement and positive emotions, which in turn positively influences learning outcomes (Makransky et al., 2019a; Makransky and Lilleholt, 2018; Parong and Mayer, 2018).

Consequently, the aim of this study was to evaluate a self-programmed IVR application and to investigate the potential of IVR training in radiology education for medical students. Specifically, the focus was on assessing student satisfaction with the IVR learning environment regarding usability, design, functions and tools and its potential effects on motivation, interest, enjoyment, engagement, learning experiences and perceived learning outcomes.

The results provide insights into the benefits and challenges of integrating IVR into medical education. The majority of students rated the handling and usability of the IVR application positively. The various interactive tools and didactic functions, such as live streaming and video recording, were also rated as useful and helpful. The usability correlated significantly with learning engagement and learning transfer, indicating that a user-friendly interface is crucial for effective learning with IVR. The significant correlations between the design, the tools and the didactic functions of the IVR application and the items related to the learning process and learning outcomes, as well as the absence of motion sickness or physical discomfort during the IVR sessions in this study, highlight the effectiveness and importance of well-designed IVR tools and the technical feasibility of using IVR in radiology education. The results are consistent with studies showing that IVR, following certain design features, can be a useful and effective teaching method in medical education without technological complexity being a barrier to learning (Rodriguez-Florida and Maynar, 2024a; Rodriguez-Florida et al., 2024b). These results are also in line with CTML (Mayer, 2009) and previous research indicating that it is not the use of IVR per se that promotes learning.

Thus, in addition to mostly positive effects, some empirical works show no effects (Di Natale et al., 2020; Hamilton et al., 2021). Two studies even report negative effects on learning (Makransky et al., 2019b; Parong and Mayer, 2018) that are ascribed to cognitive load and too many extraneous, distracting details following Cognitive Load Theory (CLT) (Sweller, 2005) and Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2009). Additionally, studies testing the same IVR application with different didactic methods found different results in knowledge and transfer between groups (Makransky et al., 2021; Meyer et al., 2019; Parong and Mayer, 2018). These findings suggest that IVR does not automatically enhance learning performance. Rather exploiting the full potential of the IVR application and its successful implementation in education depends on its careful design and meaningful didactic integration into the curriculum. Consequently, its success largely depends on how and for which learning objectives it is implemented into the curriculum (Jensen and Konradsen, 2018; Makransky et al., 2021).

In this study, the usefulness of interactive tools for engaging with the 3D visualizations correlated significantly with interest, engagement, long-term learning effects and improvement of both the learning process and radiology teaching. These results suggest that in the context of IVR-based learning, immersion and interaction features in particular are important factors for learning success, which aligns with previous research (Di Natale et al., 2020).

Furthermore, the findings of this study suggest a positive impact of IVR on affective learning characteristics. Students described that the IVR training increased their learning motivation, interest and engagement in radiology. They also indicated that they enjoyed the IVR training, highlighting its potential to foster positive achievement emotions according to CVTAE (Pekrun, 2006).

In addition, students rated the IVR-based learning as highly instructive and meaningful in supporting their learning process. They perceived the IVR training as a helpful tool for supporting their understanding of topographic anatomy and for their ability to identify anatomical structures, pathological changes and to interpret cross-sectional images. These findings are consistent with previous research demonstrating the benefits of VR in anatomy education (Bork et al., 2019; Sinha et al., 2022) and its potential to improve image interpretation skills (Wu et al., 2022). These findings imply that IVR training can effectively enhance cognitive and psychomotor learning outcomes in anatomy and radiology. Students also felt that IVR training could facilitate the learning transfer and promote long-term retention. While this pilot study cannot draw conclusions about actual long-term effects, these perceptions are in line with previous studies showing that IVR-based learning not only enhances immediate learning outcomes but also supports the retention and application of acquired knowledge and skills in practice over time (Makransky and Mayer, 2022; Wu et al., 2020). In addition, students reported that IVR training complements traditional learning methods, enhances the practical relevance of radiology education and better visualizes learning content. These findings suggest that IVR can bridge the gap between theoretical knowledge and practical application, providing a more holistic learning experience.

Limitations

While the study provides valuable insights, it also has some limitations. According to the aim of the present developmental study,

user testing was conducted and data were collected in a non-curricular setting. Although this study had a larger sample size than previous studies investigating the use of IVR in diagnostic radiology (Mustafa et al., 2024; Venson et al., 2017; Wu et al., 2022), the number of subjects was relatively small. Thus, the results are based on the perceptions of students in a small, exploratory pilot study. This limits the generalizability of the findings, particularly those of the correlation analyses. Consequently, the study cannot prove any definitive effects of IVR, but preliminary conclusions can be drawn. The sample could also be potentially biased, as mainly students with a certain basic interest in IVR and radiology may have participated in this study, which could further limit the generalizability. All variables were measured cross-sectionally with self-report ratings. Thus, the results must be interpreted cautiously.

Future directions

This design-oriented study focused on the evaluation of a self-programmed IVR application to promote students' motivation and interest in radiology and to support learning outcomes. Further research on IVR in radiology education with larger and more diverse samples as well as additional measurement methods is needed to generalize and further validate the results. In addition, longitudinal studies with a pre-posttest design and control groups are necessary to better capture and assess the effects on motivation and interest in radiology as well as the short- and long-term impact of IVR on anatomical and radiological learning outcomes. Longitudinal studies could also provide further insights into how IVR training affects clinical performance over time.

A comparison of immersive and non-immersive learning environments was not part of the study. In order to be able to make a well-founded assessment of whether IVR is a more effective teaching method in radiology compared to non-immersive visualization techniques such as a volume rendering desktop application, future comparative studies are necessary (Hamilton et al., 2021; Wu et al., 2020). In particular, a systematic analysis of the effects of both modalities on cognitive and affective factors is needed to investigate the potential added value of IVR. Studies show that intrinsic or autonomous motivation (Deci and Ryan, 2009), interest (Hidi and Renninger, 2006) and positive achievement emotions (Pekrun, 2006; Plass and Kaplan, 2016) are key predictors of long-term learning. Thus, IVR could particularly contribute to better long-term cognitive outcomes by promoting positive affective states. Consequently, in addition to measuring short- and long-term learning outcomes, especially non-cognitive outcomes are important for assessing the benefits of IVR (Makransky and Lilleholt, 2018; Wu et al., 2020). This type of study could provide evidence-based statements about the specific benefits of immersive technologies in the context of radiology teaching and thus create a sound basis for the targeted use of such applications in medical training. Additionally, IVR is rarely examined as an additional learning tool complementing traditional learning methods (Hamilton et al., 2021; Jensen and Konradsen, 2018). The actual integration of IVR applications into the curriculum is also rarely evaluated (Bork et al., 2019). To address these gaps, more research with mixed methods and longitudinal studies in real learning settings is needed.

Overall, research on IVR-based learning is still in its infancy (Hamilton et al., 2021; Makransky et al., 2019b). This applies to radiology as well as to the entire field of education. Although the number of empirical studies on IVR related to learning and education has increased substantially since 2016 (Makransky and Petersen, 2021), the majority lack a theoretical pedagogical foundation (Radianti et al., 2020). Most research focuses on students' satisfaction with the IVR application, short- to medium-term knowledge retention and, by solely using multiple-choice questionnaires, on surface knowledge. Hence, only a few studies exist on long-term effects and deeper understanding. Moreover, studies investigating learning transfer, where knowledge and skills gained in IVR are subsequently applied in practice, are scarce (Hamilton et al., 2021; Jensen and Konradsen, 2018).

Conclusion

The present study provides insights into the potential role of IVR in radiology education for medical students. In line with the limited existing work in this area (Wu et al., 2022), the findings suggest that IVR has a high potential in fostering motivation, interest, enjoyment and engagement as well as in supporting learning processes and learning outcomes. Students' positive perceptions indicate that IVR can be a promising addition to traditional learning methods and provide a more interactive and learner-centered learning experience. However, the success and effective use of IVR largely depends on the design, usability and curricular integration, supported by tailored methodological-didactic teaching concepts based on solid theoretical foundations. As a prototype evaluation, the findings are intended to inform future controlled studies. Overall, there is still a great need for further research building on the implications highlighted for future empirical work – not only in radiology teaching but in the entire field of education.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of the Philipps University of Marburg (Approval No. 24–340 BO). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LF: Project administration, Methodology, Writing – review & editing, Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Data curation. JG: Data curation, Validation, Methodology, Conceptualization, Investigation, Writing – review & editing. TT: Writing – review & editing, Supervision, Software,

Conceptualization. AM: Validation, Methodology, Investigation, Supervision, Writing – review & editing, Conceptualization.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. Open Access funding provided by the Open Access Publishing Fund of Philipps-Universität Marburg.

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.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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- The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feduc.2025.1638410/full#supplementary-material>
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