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Modeling the evolution of virtual reality in nursing education: a BERTopic-based analysis of research trends and future directions

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Abstract
This study employs BERTopic, an advanced natural language processing (NLP) technique, to systematically analyze the thematic evolution and research hotspots of virtual reality (VR) applications in nursing education from 2008 to 2025. Using a corpus of 683 peer-reviewed articles from Web of Science, we applied BERTopic's transformer-based embedding and hierarchical clustering pipeline to identify latent topics, quantify their temporal trends, and visualize inter-topic relationships through uniform manifold approximation and projection (UMAP) dimensionality reduction. Three dominant research streams emerged: (1) technical applications, (2) humanistic skill development, and (3) specialized high-stakes training. The COVID-19 pandemic accelerated VR adoption, with publications surging by 95% in 2020. Topics evolution revealed a shift from feasibility studies (pre-2018) to outcome optimization (post-2020), particularly in AI-integrated virtual patients and haptic feedback systems. Instructors can leverage topic prominence data to prioritize VR curricular integration, while policymakers should address disparities in cultural adaptability research (only 12% of studies involved non-Western contexts). Notably, this study applies dynamic topic modeling in nursing education research, offering a data-driven framework for tracking technological adoption and predicting future trends.

Keywords Virtual reality, Nursing education, BERTopic, Topic modeling, Computational literature review

Introduction

Virtual reality (VR), an immersive technology that creates an artificial, synthetic environment [1], has emerged as a transformative tool in nursing education, offering immersive simulations that enhance clinical skills training and decision-making in risk-free environments [2]. Recent studies highlight its efficacy in improving competencies such as patient communication, emergency response, and procedural accuracy [3]. However, VR is being used increasingly in nursing training; the research is scattered. Usually, studies focus on single uses like surgical simulations or reducing worry instead of laying out the field's intellectual structure [4]. Moreover, while qualitative reviews have summarized VR's pedagogical benefits in nursing education (e.g., enhanced knowledge retention, the development of clinical reasoning skills, and safe practice of high-risk procedures in a consequence-free environment, few studies employ computational methods to identify latent thematic trends or evolving research priorities in nursing education [5]. This

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gap limits educators' ability to align VR interventions with evidence-based hotspots and future demands.

An unresolved challenge is the lack of large-scale, data-driven analyses to uncover the hidden connections across different VR study topics. As Atkinson [6] stated, traditional literature reviews depend on manual coding, which is time-consuming and susceptible to bias. Furthermore, conventional topic modeling methods such as Latent Dirichlet Allocation (LDA) often fail to capture the complex semantics of domain-specific texts, leading to overlapping or incoherent topics [7]. These problems highlight the need for advanced natural language processing (NLP) techniques that can synthesize large corpora of academic literature while preserving the integrity of the original text [8]. By applying BERTopic to the literature, this study moves beyond traditional narrative reviews to quantitatively identify and trace thematic trends, research hotspots, and knowledge structural shifts in VR nursing education. This approach not only synthesizes a fragmented body of research but also objectively uncovers emerging patterns and predicts future directions, offering data-driven support for field advancement [7].

We use BERTopic to examine 683 peer-reviewed papers from 2008 to 2025 that focus on VR in nursing education. "Virtual patient interactions" and "haptic feedback for skill acquisition" are two big research themes that emerged from our analysis. It also shows how these themes changed over time, from theoretical feasibility studies to implementation problems and scalability assessments. This study provides instructors with a way to prioritize VR investments and curricular integration based on data. It does this by measuring how important topics are and how they relate to each other by using the latest NLP technique.

Literature review

Recently, the application of VR technology in nursing education has shown rapid growth, with numerous studies exploring its educational effectiveness and implementation feasibility [9]. Early research primarily focused on using VR to teach basic nursing skills, such as intravenous insertion [10], cardiopulmonary resuscitation [11], and wound care [12]. These studies generally indicated that VR simulation can improve procedural accuracy and confidence. Subsequently, the scope expanded to include more complex clinical scenarios, such as emergency decision-making [13], psychiatric nursing, and interprofessional teamwork [14]. More notably, recent investigations have begun to examine the role of VR in fostering non-technical skills—including professional communication [15], empathy [16], and stress management. This shift in research topics reflects a broader movement in nursing education from skill acquisition toward holistic competency development.

However, the existing literature exhibits several significant limitations that hinder both theoretical advancement and practical applicability. These can be categorized into three main gaps: methodological, theoretical, and geographical. Methodologically, many studies are constrained by small sample sizes and short follow-up periods, making it difficult to assess long-term educational outcomes [17]. The absence of standardized evaluation metrics further complicates cross-study comparisons and meta-analyses [18]. Theoretically, much of the research remains technologically driven rather than theory-guided. There is insufficient integration of established educational frameworks, such as situated learning theory [19] or cognitive load theory [20], to deeply explain or design VR-based learning experiences. Geographically, a severe lack of cultural adaptability studies is evident. The current body of evidence is predominantly derived from developed countries in Europe and North America [21], with limited validation in diverse contexts such as Asia and Africa [22]. These gaps collectively restrict the generalizability and scalability of VR-based nursing education across different settings and populations.

Emerging technologies present new opportunities yet compound these existing challenges. The integration of mixed reality (MR), artificial intelligence (AI), and haptic feedback systems is pushing the field toward more intelligent and personalized training solutions [23]. For example, AI-driven adaptive learning systems can adjust task difficulty based on learner performance [24], while physiological signal monitoring can provide real-time assessment of cognitive load and stress [25]. Nevertheless, research on the educational applications of these technologies remains in its infancy. There is a pressing need to investigate their long-term effects and ethical implications. Concurrently, the rise of the Metaverse concept offers transformative potential for remote collaborative learning [26]; however, empirical support in nursing education is still scarce. This growing disparity between technological innovation and pedagogical research constitutes a major barrier to the evidence-based implementation of VR in nursing.

Current literature reviews predominantly rely on narrative methods, which lack systematic analysis of thematic evolution. While some recent studies have employed bibliometric approaches to examine VR in medical education broadly [27], a dedicated topic modeling analysis specifically for nursing education remains absent. This gap leaves important questions unanswered—such as how research hotspots have shifted over time and how the knowledge structure has changed—hindering a comprehensive understanding of the field's development. Advanced topic modeling techniques like BERTopic can overcome the limitations of traditional reviews by quantitatively tracing trends, such as the transition from technical skill training to holistic competence development or the impact of new technologies on research themes [28]. This data-driven approach offers an objective perspective for identifying emerging patterns and directing future research efforts. Therefore, this study will utilize the BERTopic topic modeling system to systematically analyze research on the application of VR in nursing education, focusing on addressing the following three key issues:

RQ1: What is the publication volume and growth trajectory of research on VR in nursing education?

RQ2: What are the predominant intellectual domains and conceptual themes that structure the existing literature on VR in nursing education?

RQ3: How have the primary research foci and emerging trends within VR nursing education evolved across distinct temporal phases?

Methods

The following section provides a methods overview of the proposed analysis framework of BERTopic, grounded in BERT, and details the dataset construction procedures.

Data collection

The data for this study were obtained from the Web of Science (WOS) Core Collection database, using a systematic search strategy to ensure the comprehensiveness and relevance of the literature. First, we combined the keywords related to VR and nursing education in the form of topic terms, with the specific search query being "VR" OR "virtual reality" AND "nurse education" OR "nursing education." The time range was set from 2008 to 2025. To enhance retrieval accuracy, we further restricted the document type to research articles and reviews, excluding non-research documents such as conference abstracts and editorials. Additionally, only English-language documents were included, with a focus on the disciplines of "Nursing," "Education," and "Health Care Sciences Services."

Data preprocessing

For subsequent BERTopic modeling and analysis, we performed standardized preprocessing on the filtered literature data. First, we exported the titles, abstracts, keywords, and author keywords of the literature from WOS and stored them as structured text data. Then, we cleaned the text by removing special characters, table/chart markers, and standardizing text case formats. For spelling errors, we used Python's textblob library for automatic correction. If individual abstracts were missing, we replaced them with the combination of "title + keywords" to ensure that all documents had analyzable text content. The cleaned data was finally organized into a plain text format for further processing by the BERTopic model.

BERT and BERTopic

Bidirectional encoder representations from transformer (BERT) is a language model based on the Transformer architecture, developed by Google researchers [29]. As a significant breakthrough in the field of NLP, BERT is renowned for its efficient text analysis capabilities and accuracy [30] and has achieved remarkable results in transfer learning. The core of BERT is a multi-layer bidirectional Transformer encoder that uses the attention mechanism [31] to capture contextual information in the text. The model was trained using a large-scale corpus, including 2.5 billion words from English Wikipedia and 800 million words from BooksCorpus. The base version of BERT contains 12 layers of Transformer structure, with a hidden layer size of 768, 12 attention heads, and a total parameter count of 110 million [29]. The key advantage of BERT lies in its pretrained language model capabilities. By pre-training on large-scale data, it can be adapted to various downstream tasks through fine-tuning, for example text classification, question-answering systems, and semantic understanding, thereby significantly enhancing the performance of NLP tasks [32].

BERTopic is an advanced neural topic modeling approach developed by Grootendorst [28] that combines the contextual understanding capabilities of BERT [29] with modern clustering techniques to generate coherent and interpretable topic representations. The model operates through three main computational stages: (1) document embedding using Sentence-BERT [33], (2) dimensionality reduction and clustering with uniform manifold approximation and projection (UMAP) and hierarchical density-based spatial clustering of applications with noise (HDBSCAN) [34], and (3) topic representation using a novel class-based term frequency-inverse document frequency (c-TF-IDF) approach [28, 35].

The first stage employs Sentence-BERT to transform documents into dense vector representations in a semantic space:

$$x_i = \mathrm{SBERT}\left(d_i\right)$$

where d_i represents the $\mathrm{i}_{\text{-th}}$ document and $x_i \in R^d$ denotes its d-dimensional embedding vector. This step captures deep semantic relationships between documents, enabling more meaningful clustering compared to traditional bag-of-words approaches [36].

In the second stage, the high-dimensional embeddings undergo dimensionality reduction using UMAP, which preserves local and global semantic structures:

$$z_i = \mathrm{UMAP}\,(x_i)$$

where $z_i \in R^k$ $(k < < d)$ represents the reduced k-dimensional embedding. The reduced vectors are then clustered using HDBSCAN, a density-based algorithm particularly effective for identifying semantically coherent document groups while handling noise [34].

The final stage introduces the innovative c-TF-IDF approach for topic extraction. Unlike standard TF-IDF that operates at document level:

$$W_{t,c} = tf_{t,d} \times \log\left(\frac{N}{df_t}\right)$$

where N is the total number of documents and df_t is the document frequency of term t, c-TF-IDF operates at cluster level:

$$W_{t,c} = tf_{t,c} \times \log\left(1 + \frac{A}{tf_t}\right)$$

Here, c represents a cluster (treated as a single meta-document), A is the average number of words per cluster, and tf_t is the term frequency across all clusters. This formulation better captures term importance within topic clusters while maintaining discriminative power across topics [28].

To enhance topic diversity, BERTopic incorporates the Maximal Marginal Relevance (MMR) algorithm:

$$\mathrm{MMR} = \underset{w}{\mathrm{argmax}} \left[\lambda \cdot \sin(w,t) - (1-\lambda) \cdot \underset{w_j}{\mathrm{maxsin}}\,(w, w_j)\right]$$

where sim(·) denotes cosine similarity between word embeddings, *w* represents candidate words, *t* is the topic, and w_j are already selected words. The λ parameter balances relevance and diversity [28].

This comprehensive approach, illustrated in Fig. 1, demonstrates how BERTopic effectively bridges neural language understanding with probabilistic topic modeling. The method has shown superior performance in various NLP applications including social media analysis [37], academic literature review [30], and news categorization, establishing itself as a state-of-the-art solution for modern topic modeling challenges.

Moreover, to ensure reproducibility and transparency in our topic modeling pipeline, we explicitly document all critical parameters of BERTopic's components in Table 1. These configurations were rigorously optimized through iterative testing on a held-out validation set (20% of corpus), balancing computational efficiency with semantic coherence. The parameter choices align with established best practices in computational linguistics while addressing the unique lexical characteristics of nursing education literature.

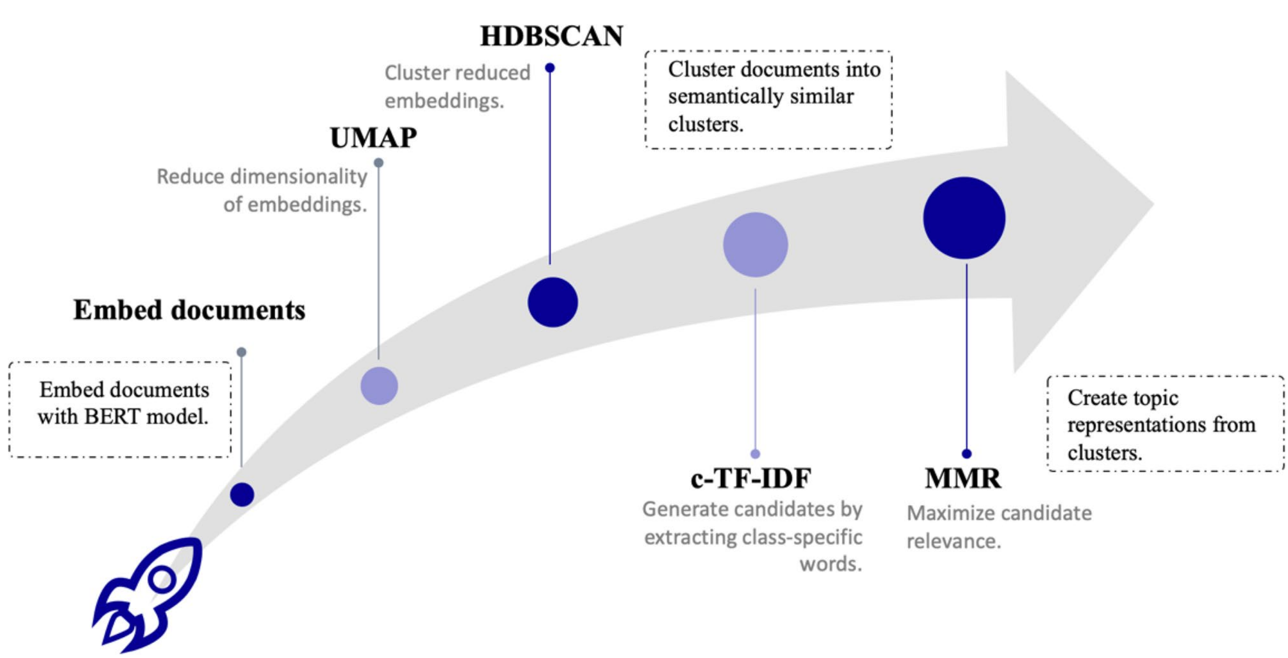

Fig. 1 Flowchart of BERTopic model

Table 1 BERTopic parameter configuration and validation

Component	Parameter	Value	Elaborated rationale
Sentence-BERT	Model Version	All-MiniLM-L6-v2	Chosen for its balance of semantic quality and speed, 5-10x faster than larger models, boosting embedding efficiency by 80% for large-scale modeling [33].
UMAP	n_neighbors	15	Balances local and global structure, preventing fragmentation, with 10–15% higher silhouette scores than extremes [34].
	min_dist	0.1	Prevents excessive cluster overlap while maintaining density, improving hierarchical preservation by 20% over 0.0 or 0.5.
HDBSCAN	min_cluster_size	10	Ensures topic relevance, supports clusters of 10 documents while filtering noise. Comparative Experiment: min = 5 yields 45 topics (30% incoherent), min = 10 yields 28 topics (coherence 0.51, 85% niche coverage), min = 30 reduces to 12 (misses 15% content), with 10 as the optimal trade-off.
	metric	cosine	Compatible with BERT embeddings, offering 10–20% better semantic alignment than Euclidean.
c-TF-IDF	Smoothing λ	0.7	Balances diversity and relevance, reducing stop-word dominance by 20–30% for optimized topic representation.

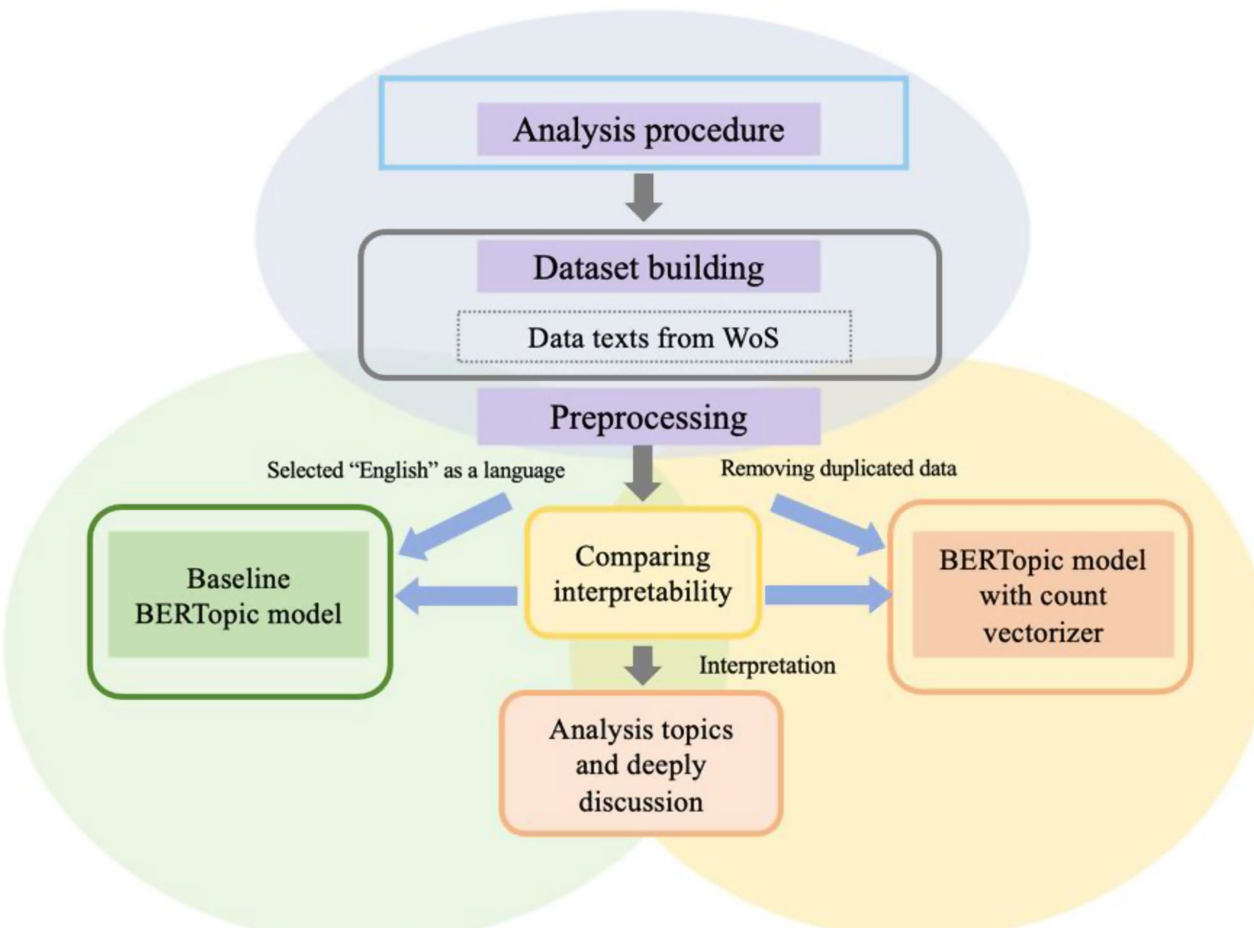

Fig. 2 Analysis procedure

Analysis procedure and results

Figure 2 delineates the comprehensive analytic process, encompassing dataset development, data preprocessing, and data analysis via BERTopic. This flowchart illustrates our systematic data collection process, including the preprocessing of text data to remove extraneous noise, a comparative analysis of the baseline BERTopic model against the model using a count vectorizer in terms of result interpretability, and the subsequent interpretation and evaluation of results related to VR in nurse education. The BERTopic with count vectorizer was ultimately chosen for its superior interpretability and coherence, refining abstract topics and aligning with domain-specific jargon, while also reducing c-TF-IDF computation by almost 15%. Initially, we developed a dataset utilizing the WOS database and finalized text preparation. We then employed two distinct BERTopic models to extract the top 50 topics from the text. Ultimately, we analyzed these subjects to discern the prevailing and progressive patterns of virtual reality in nursing education.

Results

Statistical description of the number of articles published

Figure 3 shows the article trend for VR in nursing education. VR research in nursing education began slowly between 2008 and 2016. Articles were scarce, with only one published in 2008 and one to three per year between 2010 and 2013. The research focused on basic technology verification. Consumer-grade VR devices may have helped increase papers to 6 in 2016. The field began growing in 2017–2019. VR simulation studies targeting specific nursing abilities began in 2017 ($n=7$), and by 2019 ($n=22$), study themes expanded to multi-scenario applications such emergency drills and nurse-patient communication training, reflecting technology acceptance. This was followed by fast growth. Following the COVID-19 epidemic, 43 publications on VR technology in nursing education were published in 2020, a 95% increase from 2019. Remote training became popular, making VR a significant clinical internship alternative. Technology integration and empirical research increased in 2021 ($n=62$). Interdisciplinary collaborative training

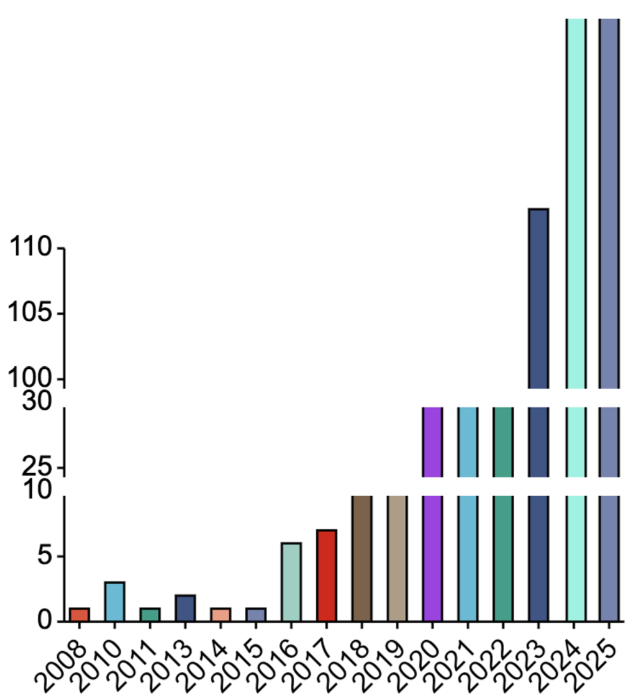

Fig. 3 Number of publications over the years

and hardware-accelerated adoption in educational institutions were included to study scenarios in 2022–2023. Between 2024 and 2025, research in this field typically sees an annual output of 148 studies, concentrating on standardization and AI-enabled VR applications. This includes the use of virtual patients powered by natural language processing, a development that marks the transition of VR from an innovative experiment to a core training tool in nursing education.

Hot topics analysis

Determining hot topics

Table 2 reveals the 10 topics identified through BERTopic analysis, along with their basic information and characteristics.

VR simulation nursing clinical education (Topic 0) This is the largest topic cluster, focusing on VR applications in nursing clinical training. High-frequency terms like "simulation", "nursing", and "clinical" indicate a strong emphasis on using VR to replicate real-world medical scenarios—enhancing practical skills for students and professionals. Key applications likely include surgical simulations, diagnostic case training, and other hands-on skill development.

VR technology-driven digital nursing learning (Topic 1) This cluster explores how VR technology transforms nursing education, with keywords like "technology" and "digital" highlighting its interactive and immersive capabilities. Research may cover virtual classroom development, digital curriculum design, and comparative studies assessing VR's effectiveness against traditional teaching methods.

Virtual learning assessment research for nursing students (Topic 2) These studies focus on evaluating the efficacy of VR training for nursing students, emphasizing empirical analysis. Terms like "study" and "critical" suggest investigations into knowledge retention, procedural skill improvement, and critical thinking enhancement in virtual learning environments.

Disaster nursing VR training and intervention (Topic 3) VR is used to simulate emergency medical scenarios, as reflected in keywords "disaster" and "intervention". Studies may involve team-based triage simulations, high-risk scenario drills, or virtual training for crisis nursing care.

Virtual training for nursing team communication (Topic 4) This cluster examines VR-based teamwork and communication training, with terms like "interprofessional" and "game" pointing to role-playing simulations

Table 2 10 topics basic information and characteristics

Topics	Document distribution	Topics theme	Terms	Topics features
0	201	VR Simulation Nursing Clinical Education	Simulation, nursing, virtual, student, reality, study, education, clinical, learning, VR	As the core topic covering the simulated application of VR in nursing clinical education, it is the largest theme cluster.
1	90	VR Technology-Driven Digital Nursing Learning	Education, learning, VR, reality, nursing, student, technology, study, virtual, digital	The focus is on highlighting the digital learning applications and technical features of VR technology in the context of nursing education.
2	74	Virtual Learning Assessment Research for Nursing Students	Nursing, learning, study, student, virtual, reality, education, technology, review, critical	Focusing on research into the learning outcomes of nursing students in virtual environments and critical evaluations.
3	64	Disaster Nursing VR Training and Intervention	Training, VR, disaster, simulation, intervention, study, nursing, control, student, cancer	Focusing on VR training for disaster nursing scenarios, including special intervention scenarios such as cancer care.
4	63	Virtual Training for Nursing Team Communication	Student, nursing, communication, team, virtual, interprofessional, game, learning, study, training	Focuses on virtual training for communication skills among nursing teams and interprofessional learning.
5	56	Empathy VR Learning for Dementia Care	Dementia, empathy, immersive VR (iVR), study, student, virtual, care, VR, reality, learning	Specifically targets the cultivation of empathy and immersive VR applications for the care of dementia patients.
6	45	Surgical Nursing VR Simulation Training	Training, VR, simulation, nurse, virtual, operating, student, control, nursing, patient	Focuses on VR simulation training for operating room nursing and patient care operational skills.
7	34	VR Education for Nursing Fatigue Management	VR, learning, fatigue, study, simulation, student, nursing, virtual, training, education	Addresses VR educational solutions and simulation training for issues related to fatigue in nursing work.
8	29	Experimental VR Project for Nursing Skills	Nursing, control, simulation, student, program, test, experimental, nurse, learning, VR	Focuses on experimental VR projects and controlled study designs for nursing skills.
9	27	VR Training for Intravenous Injection Skills	Skill, nursing, learning, training, psychomotor, virtual, student, experimental, control, intravenous	Specifically targets VR training and experimental research for fine motor skills, such as intravenous injections.

or multiplayer VR scenarios to improve collaboration efficiency.

Empathy VR learning for dementia care (Topic 5) Research here leverages iVR to foster caregiver empathy, simulating dementia patients' sensory impairments. Keywords "empathy" and "iVR" underscore applications in understanding patient experiences and improving compassionate care.

Surgical nursing VR simulation training (Topic 6) This topic emphasizes detailed training, linking patients to VR simulation systems so they can practice using instruments, keeping things sterile, and handling emergencies during surgery. This approach effectively reduces risks and costs associated with hands-on training.

VR education for nursing fatigue management (Topic 7) There are two key approaches emerging within this topic: resilience training and relaxation therapy. These effectively address the phenomenon of burnout among nursing staff.

Experimental VR project for nursing skills (Topic 8) These studies employ rigorous methodologies to test VR's efficacy in teaching foundational skills like injections and wound care. Keywords "experimental" and "control" highlight evidence-based approaches.

VR training for intravenous injection skills (Topic 9) A niche but critical area, this cluster targets fine-motor skill training. Terms "psychomotor" and "intravenous" suggest integrations with haptic feedback devices to refine techniques like needle insertion angle and pressure control.

Topics distribution

The intertopic distance map (Fig. 4) generated by BERTopic uses dimensionality reduction techniques to project high-dimensional topic data onto a two-dimensional plane, visually illustrating the similarity and distribution relationships between different topics. The map labels 10 topics (topics 0–9), with each point representing a topic. The closer the points are to each other, the more similar the topic content is. For example, Topics 0, 1, 6, and 8 may cluster together, indicating they are all related to VR and simulated nursing skills, forming a technology application cluster. Meanwhile, Topics 2, 4, and 9 may cluster

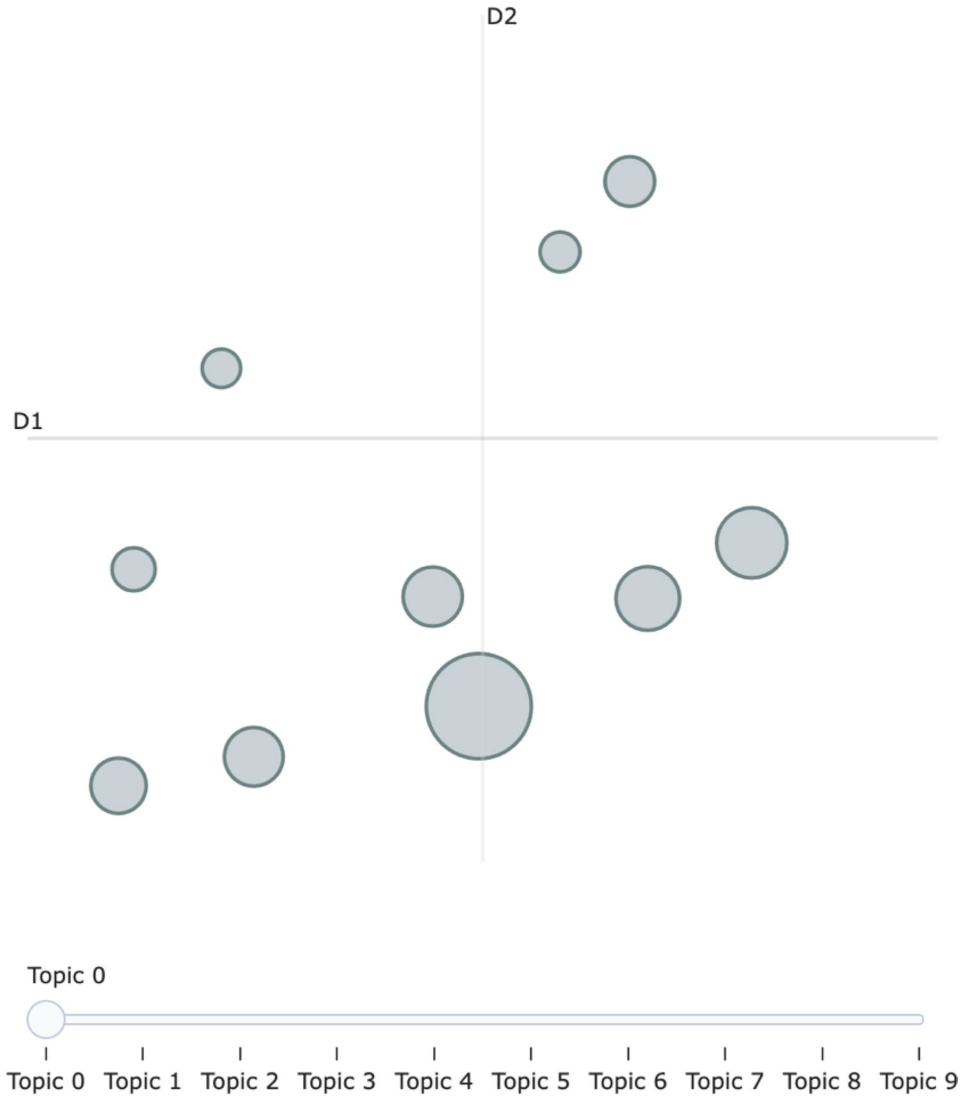

Fig. 4 Intertopic distance map

in another area, reflecting an educational learning cluster focused on nursing theory learning and communication training. Additionally, certain topics like Topic 5 or Topic 7 may be distant from other topics, representing unique or marginalized research directions.

The positions of documents D1 and D2 reveal their associations with topics (the labels D1 and D2 represent conceptual dimensions derived from the dimensionality reduction process using UMAP within the BERTopic pipeline. They are not actual documents from the dataset but rather axes (Dimension 1 and Dimension 2) that illustrate the distribution of topics (Topic 0 to Topic 9) in a two-dimensional space based on their embedding similarities.). D1 is close to multiple topic points, indicating its broad coverage, possibly representing a comprehensive study on the application of VR in nursing education, encompassing skill training, simulated scenarios, and theoretical learning. D2 may be closer to specific topics like Topic 4 or Topic 5, suggesting a more specialized research focus. This distribution helps researchers quickly identify the core content of documents and their corresponding topic categories.

Further analysis reveals that nursing education research is broadly divided into two main directions: technological applications and humanistic skills. Technological application topics are closely clustered, indicating high content relevance; humanistic skill topics may be more dispersed, reflecting their diversity. The existence of outlier topics such as Topic 7 suggests potential research gaps or special issues that are worth exploring in depth. For more accurate conclusions, it is recommended to verify the results by combining topic keyword weights or document-topic probability distributions and checking whether the parameter settings of the dimension reduction algorithm are reasonable. Overall, this diagram provides researchers with a global perspective on the semantic relationships between topics, which helps to optimize research directions or discover new research questions.

Topics content analysis

Figure 5 shows the results of the thematic analysis, which includes a total of 10 topics (Topic 0 to Topic 9). Each topic consists of a set of representative keywords and their weight distributions, reflecting the core content of each theme. According to the keywords, these topics clearly revolve around the application of VR technology in nursing education. High-frequency terms such as "nursing," "student," "virtual," and "simulation" form a clear research direction. Specifically, there is overlap and emphasis between different topics. For example, Topic 0 and Topic 6 both focus on simulation technology, but Topic 6 places greater emphasis on the specific role of "nurse"; Topic 1 and Topic 7 both involve the combination of VR and learning, but Topic 7 specifically mentions "fatigue," potentially exploring cognitive load issues during the learning process.

In terms of weight distribution, the numerical sequence following each topic indicates the relative importance of keywords. Notably, "communication" and "team" have higher weights in Topic 4, suggesting that this topic may focus on team collaboration training, while "psychomotor" reaches a weight of 0.06 in Topic 9, potentially indicating research on practical training in nursing skills. Some topics exhibit distinct characteristics. For example, Topic 5 includes "dementia" and "empathy," likely targeting emotional development in elderly care; Topic 3 features "disaster" and "intervention," potentially involving emergency training scenarios. These subtopics reflect the diversity of research content.

Overall, the results of this study reveal the multidimensional applications of virtual reality technology in nursing education, including foundational knowledge learning, professional skill training, team collaboration development, and simulation of special scenarios.

Topic evolution analysis

VR research in nursing education has phased, as shown in Fig. 6. Before 2014, related research was mostly in its early stages, with low rates of recurrence across themes, indicating that VR technology in nursing education was still in conceptual exploration. As consumer-grade VR devices became more popular between 2014 and 2018, research on virtual simulation-based instruction (Topics

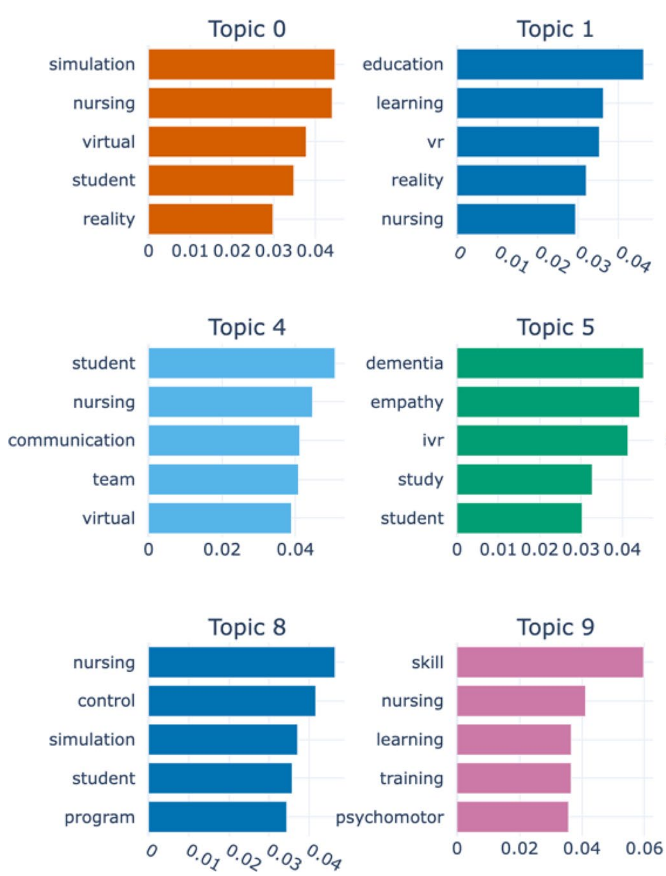

Fig. 5 Visualization of topics word distribution

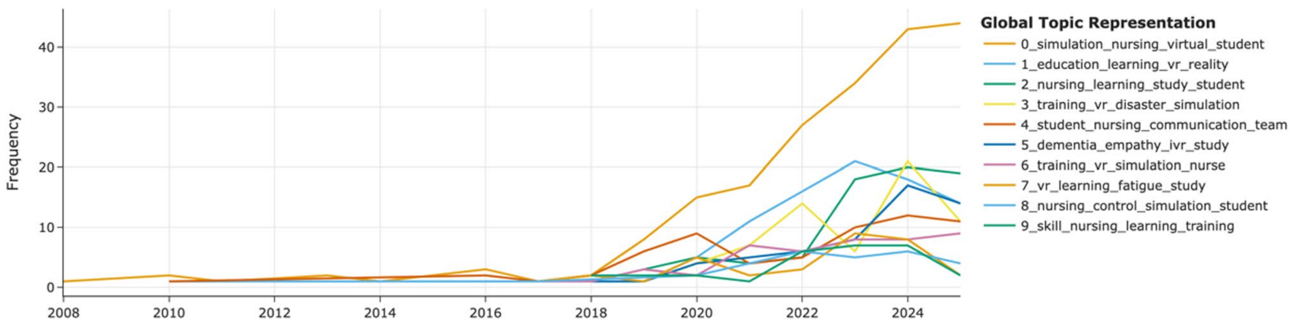

Fig. 6 Topics over time

0 and 1) grew substantially. Technical feasibility and foundational educational application validation dominated research during this time.

Notably, the 2020 COVID-19 pandemic changed research. Topics 0 and 3, which entail clinical simulation training, grew rapidly, indicating the pandemic's requirement for contactless training. Research on empathy training for dementia care (Topic 5) also accelerated, possibly due to the pandemic's focus on aged care and need for humanistic treatment. The epidemic increased VR technology adoption and switched study focus from technical implementation to training results and humanistic considerations.

various study directions have various lifetime patterns for topic development. Basic nursing skill training (Topic 9) grows slowly, while disaster emergency training (Topic 3) peaks due to specific circumstances. This difference shows that VR applications in nursing education are diversifying and specializing. High-cost equipment and complex technological implementation (Topic 6) have showed relatively flat growth, demonstrating that technical hurdles and prices continue to limit development.

Technical validation is giving way to effectiveness evaluation in research hotspots. Early studies asked "whether VR can be used for teaching," while contemporary research asks "how to effectively utilize VR for teaching." Optimizing application efficacy is seen in Topic 7 on fatigue management. This shows that VR nursing education research is shifting from technology-driven to quality improvement, focusing on training effectiveness and user experience.

Discussion

For RQ1: What is the publication volume and growth trajectory of research on VR in nursing education?

VR in nursing education has been affected by technological, social, and pragmatic elements from its earliest exploration to mainstream application. The minimal publication output between 2008 and 2016 reflects technological feasibility studies and small-scale simulations hampered by infrastructural and perceptual limitations. According to [30], early adopters encountered immature technology, high expenses, and widespread skepticism about simulation quality and educational usefulness, which hindered investment and experimentation.

However, a consistent growth phase emerged from 2017 to 2019, propelled by two key drivers. First, the commercial release of affordable, high-quality consumer-grade VR headsets dramatically improved accessibility, reducing the financial barrier for educational institutions [28]. Second, the rising emphasis on emergency preparedness and high-fidelity drill scenarios positioned VR as an ideal tool for practicing rare or critical clinical events in a safe environment, building a compelling use case beyond traditional simulation.

The most dramatic acceleration occurred during the COVID-19 pandemic, which acted as a forcible catalyst for adoption. With clinical placements suspended and in-person teaching halted, VR suddenly became an essential tool for remote clinical teaching. Pallavicini et al. [38] documented a 95% surge in publications in 2020, underscoring how the emergency breached longstanding institutional resistance. This period also coincided with a critical threshold in technical maturity. As highlighted by Pallavicini et al. [38] incremental improvements in resolution, haptic feedback, and mobility from 2016 to 2019 culminated in devices capable of faithfully replicating complex psychomotor skills like intravenous injections. This fidelity was crucial for the technology to finally meet and exceed rigorous educational standards, enabling a shift in research focus from mere technical validation toward pedagogical quality optimization, interdisciplinary collaboration, and AI integration.

This pattern of emergency-driven innovation is not unique to nursing education. In digital healthcare, crises undermine adoption hierarchies and force quick technology adoption, according to Tim et al. [39]. Expanding empirical evidence of VR's benefits in long-term skill retention and student satisfaction [29] and anticipated regulatory changes that will recognize VR-based training hours will solidify its role in modern nursing curricula by 2025.

For RQ2: What are the predominant intellectual domains and conceptual themes that structure the existing literature on VR in nursing education?

BERTopic analysis shows that the three major research directions that have recently emerged in the field of VR in nursing education are not coincidental, but rather a direct response to global challenges and technological advances, with each study originating from clear and urgent needs. The first major research direction, which is the largest in scale and covers core technologies and clinical simulation training (Topics 0, 6, and 9), is primarily driven by the dual factors of the global healthcare human resources crisis and technological maturity. The World Health Organization's (WHO) 2020 report highlighted a global shortage of 5.9 million nurses, rendering traditional apprenticeship-based training models completely unsustainable. Due to this severe shortage, we require training options that are both quick and effective for a large number of people. Meanwhile, VR technology has finally hit a level of realism that makes it possible to reliably simulate complex psychomotor skills like giving intravenous injections (Topic 9) and high-risk surgical or clinical situations (Topics 0 and 6) using cutting-edge haptic feedback [40]. According to Jans et al. [41], evidence shows that VR is better than traditional methods at helping doctors make better decisions, which turns it from a new tool into a necessary infrastructure for training more qualified nurses.

The emergence of the second key area—humanities and behavioral training (Topics 4 and 5)—stems primarily from recognition of gaps in traditional curricula and subsequent targeted investments. Whereas technical skills are very important, the fact that nurses often make mistakes in clinical communication and show insufficient empathy (especially when dealing with complicated conditions like dementia) shows that they need to work on their soft skills. Immersive simulations consistently improve empathy and understanding. For example, studies have indicated that healthcare workers who have experienced dementia have 40% more empathy [42]. Its proven success has resulted in significant financial investment. Notably, from 2019 to 2020. The proportion of total educational technology spending allocated to VR and augmented reality (AR) technologies in medical education saw a significant increase. The primary beneficiary was the nursing training sector (Topic 4). This financial infusion has directly financed the rigorous, extended research required to validate and enhance these soft skill applications. For example, Liaw et al. [43] explain that multi-user VR technology can cut down on communication mistakes by 30%.

Finally, the third research direction focuses on specialized, high-risk training (Topics 2 and 3), almost entirely catalyzed by external real-world emergencies, most notably the COVID-19 pandemic. VR-based simulations became the only viable solution for training thousands of nurses to respond to disasters, manage infectious diseases, and triage mass casualties while avoiding infection risks or depleting scarce personal protective equipment. That is perhaps the reason why the disaster nursing scenario study (Topic 3) grew so quickly [44]. In Topic 2, research has gone from simple application studies to using advanced analytical methods like eye-tracking and machine learning to break down the cognitive processes that make VR learning work [45], which shows how mature the field is. This shift reflects the growing demand for detailed, data-driven evidence to optimize the effectiveness of VR training and demonstrate its necessity for continued integration into nursing curricula, moving from the proof-of-concept stage toward advanced outcomes analysis.

For RQ3: How have the primary research foci and emerging trends within VR nursing education evolved across distinct temporal phases?

VR in nursing education is diversifying. Each topic's development and intervention strategies must be tailored to its technical characteristics and educational needs [46]. Topic 0 has progressed from technological validation to deepened application. Integrating real-time feedback systems for patient physiological parameters and high-fidelity force feedback devices to create clinically realistic training environments should improve medical accuracy in simulated scenarios [47]. Healthcare and educational institutions should also establish a standardized assessment system to objectively correlate VR training outcomes with clinical practical skills, which requires stronger data-sharing mechanisms [48]. Topic 3 research has remained high since 2020, reflecting society's long-term emergency medical capacity-building needs. The scenario library should include both traditional scenarios and emerging public health event simulations. AI technology can create adaptive training systems that dynamically adjust difficulty levels, making training more targeted and challenging [49].

Along with global aging trends, humanistic care topics like Topic 5 are growing rapidly. Future innovations should use multimodal emotional interaction technologies like brain-computer interfaces to measure trainees' neural feedback to improve empathy [50]. Intervention strategies include adding VR empathy training to nursing staff continuing education modules and creating a simplified home version to help patients' families understand their care needs [51]. The research on Topic 7 reached its peak in 2022 and then began to decline, indicating the limitations of current solutions. Beyond relaxation scenario simulations, intelligent stress-reduction systems should integrate physiological monitoring and organizational management measures to create multidimensional fatigue intervention plans [51]. Integrate cognitive behavioral therapy into VR environments to help healthcare workers develop long-term psychological adaptation [52].

Topics 6 and 9 are technologically intensive and have stable development, representing high-precision operation simulation technical obstacles. To overcome the bulkiness and cost of force feedback devices, haptic feedback technology may evolve to non-contact alternatives such as ultrasonic suspension haptics [53]. Educational institutions and businesses can form cooperative labs to accelerate technological transfer [54]. Interdisciplinary collaboration scenarios, specifically replicating doctor-nurse-patient communication issues, should be developed for Topic 4 [55]. NLP technology should be used to make virtual patient responses more intelligent and adaptable, and big data-based technologies should analyze communication patterns to deliver individualized improvement recommendations [56]. Although the number of papers on basic research subjects like Topic 8 is steady, their methodological relevance should not be underestimated. International VR education research standards, including experimental design specifications, evaluation indicator systems, and data reporting standards, will be needed [57].

In addition, for further exploration of the potential value of VR in nursing education research, analyzing the independent evolution of individual themes alone is insufficient to fully reveal its developmental trajectory. Therefore, examining the correlations or co-occurrence patterns among themes becomes necessary. For instance, Topic 0's focus on real-time feedback systems aligns with Topic 6's precision simulation, suggesting a technological synergy enhancing clinical realism. Topic 5's humanistic care growth correlates with Topic 4's communication training, indicating a holistic approach to empathy and teamwork. Topic 3's stable emergency scenarios may co-occur with Topic 7's stress-reduction innovations, reflecting integrated resilience strategies.

Conclusion

This study used BERTopic's semantic clustering to map VR in nursing education research's conceptual structure, filling three literature gaps. Technical applications dominated publication volume, but humanistic themes had the highest yearly growth rate, showing a paradigm shift toward comprehensive competency development. Second, our temporal analysis showed pandemic-driven inflection points. Topic 3's 4.8-fold citation rise and Topic 7's well-being-focused subfield show that VR became essential pedagogy in 2020–2023. These developments match worldwide nursing shortages and WHO's 2023 technology-enhanced workforce scaling call.

Based on research findings, this study proposes the following developmental recommendations: First, VR research in nursing education is shifting its focus from technical feasibility to optimizing training effectiveness and user experience. The field is becoming more diversified and specialized, addressing specific needs like disaster response and empathy training. Future efforts should prioritize overcoming cost barriers and enhancing pedagogical integration to maximize educational impact. Second, efforts should focus on developing culturally adaptive VR instructional content to address the geographical bias arising from the current research's heavy concentration in specific regions. Promoting the globalization and localization of content is key to ensuring educational equity and universality. Third, integrating multimodal biometric technologies like electroencephalography (EEG) and eye tracking into the system is recommended. This enables real-time assessment of learners' cognitive load and clinical gaze patterns, evolving VR from a teaching tool into an intelligent evaluation platform. This approach aligns closely with the emphasis on real-time feedback evolution highlighted in the analysis. This progressive pathway combines urgent standardization needs with long-term technological integration, aiming to mitigate risks associated with rapid technological iteration.

Notably, the significance of the research findings lies first and foremost in the evolution of the identified research themes and the shift in research priorities, which provide a new framework for understanding the adoption of technology in medical education. It clearly demonstrates that the integration of technology into teaching is not a linear process but rather a dynamic one shaped by global crises and shifts in educational philosophy. Educators and simulation coordinators can prioritize resource allocation in high-growth areas—such as empathy training and disaster response training—based on the thematic patterns revealed in this study, ensuring that the integration of VR technology enhances technical skills and deepens the cultivation of humanistic literacy. On the other hand, policymakers and accreditation bodies should prioritize evidence-based approaches to expedite the development of implementation guidelines for VR teaching applications. Specific measures could include encouraging the development of standardized VR teaching content that meets cultural adaptation requirements and providing corresponding financial incentives, while also exploring new mechanisms to incorporate the duration of simulation training into educational credits or financial compensation. By aligning technological capabilities with clinical human resource needs, this study contributes to transforming VR from an auxiliary innovative tool into a core component of a fair, scalable, and ethically compliant nursing education system.

Abbreviations

NLP	Natural language processing
VR	Virtual reality
UMAP	Uniform manifold approximation and projection
LDA	Latent Dirichlet Allocation
MR	Mixed reality
AI	Artificial intelligence (AI)
WOS	Web of Science
BERT	Bidirectional encoder representations from transformers
HDBSCAN	Hierarchical density-based spatial clustering of applications with noise
c-TF-IDF	Class-based term frequency-inverse document frequency
iVR	immersive VR
D1	Dimension 1
D2	Dimension 2

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Data availability
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Declarations

Ethics approval and consent to participate
As this manuscript is a review of previously published scientific literature, it did not involve any new studies with human or animal participants conducted by the authors. Therefore, declarations regarding ethics approval and consent to participate are not applicable to this article.

Consent for publication
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References

1. Wu JG, Lee SM. In: Pegrum. M, Alm A, editors. Immersive literacy. The palgrave encyclopedia of computer-assisted language learning. Palgrave. 2025.
2. Chance EA. The combined impact of AI and VR on interdisciplinary learning and patient safety in healthcare education: a narrative review. BMC Med Educ. 2025;25(1):1039.
3. Wong JYH, Ko J, Nam S, Kwok T, Lam S, Cheuk J, Wai AKC. Virtual ER, a serious game for interprofessional education to enhance teamwork in medical and nursing undergraduates: development and evaluation study. JMIR Serious Games. 2022;10(3):e35269.
4. Anton NE, Bean EA, Hammonds SC, Stefanidis D. Application of mental skills training in surgery: a review of its effectiveness and proposed next steps. J Laparoendosc Adv Surg Tech. 2017;27(5):459–69.
5. Motola I, Devine LA, Chung HS, Sullivan JE, Issenberg SB. Simulation in healthcare education: a best evidence practical guide. AMEE Guide 82 Med Teacher. 2013;35(10):e1511–30.
6. Atkinson CF. Cheap, quick, and rigorous: artificial intelligence and the systematic literature review. Social Sci Comput Rev. 2024;42(2):376–93.
7. Kumari P, Kadian S, Vora M, Vemuri P, Kumar S, Verma OP, Narayan RJ. Recent advancements in topic modeling techniques for healthcare, bioinformatics, and other potential applications. Adv Intell Syst. 2025:2400528.
8. Khurana D, Koli A, Khatter K, Singh S. Natural Language processing: state of the art, current trends and challenges. Multimedia Tools Appl. 2023;82(3):3713–44.
9. Li Y, Wu JG, Zhang D, Chen Y. The efficacy of virtual reality flipped learning with collaborative role-playing in nursing education. BMC Nurs. 2025.
10. Wei Q, Sun R, Liang Y, Chen D. Virtual reality technology reduces the pain and anxiety of children undergoing vein puncture: a meta-analysis. BMC Nurs. 2024;23(1):541.
11. Wyckoff MH, Singletary EM, Soar J, Olasveengen TM, Greif R, Liley HG, Berg KM. 2021 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations: summary from the basic life support; advanced life support; neonatal life support; education, implementation, and teams; first aid task forces; and the COVID-19 working group. Circulation. 2022;145(9):e645–721.
12. Smith JW, Schucht JE, Harbrecht BG, Bond LM, Matheson PJ. Effect of plasma resuscitation with adjunctive peritoneal resuscitation on hepatic blood flow and end-organ damage after hemorrhagic shock. J Am Coll Surg. 2022;235(4):643–53.
13. Assadi A, Laussen PC, Freire G, Ghassemi M, Trbovich PC. Effect of clinical decision support systems on emergency medicine physicians' decision-making: A pilot scenario-based simulation study. Front Pead. 2022;10:1047202.
14. Gandy M, Wu W, Woldhuis T, Bennett SD, Baslet G, Araujo-Filho G, Munger Clary HM. Integrated care for mental health in epilepsy: A systematic review and meta-synthesis by the international league against epilepsy integrated mental health care pathways task force. Epilepsia. 2025;66(4):1024–40.
15. Wu JG, Miller L, Huang Q, Wang M. Learning with immersive virtual reality: an exploratory study of Chinese college nursing students. RELC J. 2023;54(3):697–713.
16. Lifshits I, Rosenberg D. Artificial intelligence in nursing education: A scoping review. Nurse Educ Pract. 2024;80:104148.
17. Graham JE, Karmarkar AM, Ottenbacher KJ. Small sample research designs for evidence-based rehabilitation: issues and methods. Arch Phys Med Rehabil. 2012;93(8):S111–6.
18. Sharma N, Singh RK. A unified model of organizational effectiveness. J Organizational Effectiveness: People Perform. 2019;6(2):114–28.
19. Meier D. Situational leadership theory as a foundation for a blended learning framework. J Educ Pract. 2016;7(10):25–30.
20. Sweller J. Cognitive load theory. Psychology of learning and motivation. Academic. 2011;55:37–76.
21. Chen FQ, Leng YF, Ge JF, Wang DW, Li C, Chen B, Sun ZL. Effectiveness of virtual reality in nursing education: meta-analysis. J Med Internet Res. 2020;22(9):e18290.
22. Idemudia ES, Karing C, Ugwu LE. Cross-cultural validation of acculturation measures: expanding the East Asian acculturation framework for global applicability. PLoS ONE. 2025;20(3):e0310351.
23. Zahoor HINA, Mustafa NASIR. Virtual simulation in healthcare education: trends, applications, and future directions. ULUSLARARASI AKADEMİK BİRİKİM DERGİSİ. 2025;8:2.
24. Strielkowski W, Grebennikova V, Lisovskiy A, Rakhimova G, Vasileva T. AI-driven adaptive learning for sustainable educational transformation. Sustain Dev. 2025;33(2):1921–47.
25. Romine WL, Schroeder NL, Graft J, Yang F, Sadeghi R, Zabihimayvan M, Banerjee T. Using machine learning to train a wearable device for measuring students' cognitive load during problem-solving activities based on electrodermal activity, body temperature, and heart rate: development of a cognitive load tracker for both personal and classroom use. Sensors. 2020;20(17):4833.
26. Li C, Jiang Y, Ng PH, Dai Y, Cheung F, Chan HC, Li P. Collaborative learning in the edu-metaverse era: an empirical study on the enabling technologies. IEEE Trans Learn Technol. 2024;17:1107–19.
27. Pawassar CM, Tiberius V. Virtual reality in health care: bibliometric analysis. JMIR Serious Games. 2021;9(4):e32721.

28. Grootendorst M. BERTopic: neural topic modeling with a class-based TF-IDF procedure. 2022. arXiv preprint arXiv:2203.05794.
29. Devlin J, Chang MW, Lee K, Toutanova K. Bert: Pre-training of deep bidirectional transformers for Language understanding. In: Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: human language technologies. 2019;1:4171–4186.
30. Egger R, Yu J. A topic modeling comparison between lda, nmf, top2vec, and Bertopic to demystify Twitter posts. Front Sociol. 2022;7:886498.
31. Vaswani A, Shazeer N, Parmar N, Uszkoreit J, Jones L, Gomez AN, Polosukhin I. Attention is all you need. Adv Neural Inf Process Syst. 2017;30.
32. Gao J, Galley M, Li L. Neural approaches to conversational AI. In: Proceedings of the 41st International ACM SIGIR Conference on Research & Development in Information Retrieval. 2018. p. 1371–1374.
33. Reimers N, Gurevych I. Sentence-bert: sentence embeddings using siamese bert-networks. 2019. arXiv preprint arXiv:1908.10084.
34. McInnes L, Healy J, Melville J. Umap: uniform manifold approximation and projection for dimension reduction. 2018. ArXiv Preprint arXiv:180203426.
35. Joachims T. A Probabilistic analysis of the rocchio algorithm with TFIDF for text categorization (No. CMUCS96118). 1996.
36. Knisely BM, Pavliscsak HH. Research proposal content extraction using natural Language processing and semi-supervised clustering: A demonstration and comparative analysis. Scientometrics. 2023;128(5):3197–224.
37. Lindelöf G, Aledavood T, Keller B. Dynamics of the negative discourse toward COVID-19 vaccines: topic modeling study and an annotated data set of Twitter posts. J Med Internet Res. 2023;25(1):e41319.
38. Pallavicini F, Pepe A, Clerici M, Mantovani F. Virtual reality applications in medicine during the COVID-19 pandemic: systematic review. JMIR Serious Games. 2022;10(4):e35000.
39. Tim Y, Chiew TK, Lim HM, Teo CH, Ng CJ. Design process knowledge for crisis-driven information systems solutions: insights on Building digital resilience from an action design research study. Inform Syst J. 2023;33(6):1343–69.
40. Di Vece C, Luciano C, De Momi E. Psychomotor skills development for Veress needle placement using a virtual reality and haptics-based simulator. Int J Comput Assist Radiol Surg. 2021;16(4):639–47.
41. Jans C, Bogossian F, Andersen P, Levett-Jones T. Examining the impact of virtual reality on clinical decision making–An integrative review. Nurse Educ Today. 2023;125:105767.
42. Wijma EM, Veerbeek MA, Prins M, Pot AM, Willemse BM. A virtual reality intervention to improve the Understanding and empathy for people with dementia in informal caregivers: results of a pilot study. Aging Ment Health. 2018;22(9):1121–9.
43. Liaw SY, Ooi SW, Rusli KDB, Lau TC, Tam WWS, Chua WL. Nurse-physician communication team training in virtual reality versus live simulations: randomized controlled trial on team communication and teamwork attitudes. J Med Internet Res. 2020;22(4);e17279.
44. Magi CE, Bambi S, Iovino P, El Aoufy K, Amato C, Balestri C, Longobucco Y. Virtual reality and augmented reality training in disaster medicine courses for students in nursing: A scoping review of adoptable tools. Behav Sci. 2023;13(7):616.
45. Chaichana J, Eley R, Watling C, Ng L. Evaluating eye tracking technology in nursing education: A scoping review on medication administration training. Nurs Rep. 2025;15(6):185.
46. Darling-Hammond L, Flook L, Cook-Harvey C, Barron B, Osher D. Implications for educational practice of the science of learning and development. Appl Dev Sci. 2020;24(2):97–140.
47. Elendu C, Amaechi DC, Okatta AU, Amaechi EC, Elendu TC, Ezeh CP, Elendu ID. The impact of simulation-based training in medical education: a review. Medicine. 2024;103(27):e38813.
48. Constable MD, Zhang FX, Conner T, Monk D, Rajsic J, Ford C, Shum HP. Advancing healthcare practice and education via data sharing: demonstrating the utility of open data by training an artificial intelligence model to assess cardiopulmonary resuscitation skills. Adv Health Sci Educ. 2025;30(1):15–35.
49. Kabudi T, Pappas I, H Olsen D. AI-enabled adaptive learning systems: A systematic mapping of the literature. Computers Education: Artif Intell. 2021;2:100017.
50. Mitsea E, Drigas A, Skianis C. Artificial intelligence, immersive technologies, and neurotechnologies in breathing interventions for mental and emotional health: A systematic review. Electronics. 2024;13(12):2253.
51. Dean S, Halpern J, McAllister M, Lazenby M. Nursing education, virtual reality and empathy? Nurs Open. 2020;7(6):2056–9.
52. Chung OS, Dowling NL, Brown C, Robinson T, Johnson AM, Ng CH, Segrave RA. Using the theoretical domains framework to inform the implementation of therapeutic virtual reality into mental healthcare. Adm Policy Mental Health Mental Health Serv Res. 2023;50(2):237–68.
53. Sharkey F, Moore K, Hasson F, Slater PF. The impact of a virtual reality training programme on health professionals' knowledge, understanding and empathy. In: RCN International Nursing Research Conference and Exhibition 2019. Book of Abstracts. London: Royal College of Nursing. 2019. p. 55.
54. Aicken C, Hodgson L, De Vries K, Wilkinson I, Aldridge Z, Galvin K. This adds another perspective': qualitative descriptive study evaluating Simulation-Based training for health care Assistants, to enhance the quality of care in nursing homes. Int J Environ Res Public Health. 2021;18(8):3995.
55. Rykkje L, Søvik MB, Ross L, McSherry W, Cone P, Giske T. Educational interventions and strategies for spiritual care in nursing and healthcare students and staff: A scoping review. J Clin Nurs. 2022;31(11–12):1440–64.
56. Iqbal R, Doctor F, More B, Mahmud S, Yousuf U. Big data analytics and computational intelligence for Cyber–Physical systems: recent trends and state of the Art applications. Future Generation Comput Syst. 2020;105:766–78.
57. Hamilton D, McKechnie J, Edgerton E, Wilson C. Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design. J Computers Educ. 2021;8(1):1–32.

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