Development and Pre-Validation of a Gamified Virtual Reality Platform for SPECT Education and Training with Biomedical Engineering Metrics Integration

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Abstract: Single Photon Emission Computed Tomography (SPECT) is a nuclear medicine imaging modality widely used in cardiology, neurology, and oncology. However, its teaching in Biomedical Engineering, Medical Imaging and Radiotherapy, and Medicine programmes remains largely dependent on traditional methods, constrained by limited access to Gamma Cameras and workstations, high operational costs, and restrictions related to ionising radiation exposure. Virtual Reality (VR) offers a promising alternative for immersive, safe, and repeatable training environments. Nevertheless, dedicated SPECT educational platforms that integrate realistic simulation, gamification strategies, and quantitative performance assessment remain scarce. This work presents the conceptual design of a gamified VR-based training framework for SPECT education, to be developed in Unity for Meta Quest 3. The system simulates key stages of the SPECT workflow. It also incorporates equipment interaction and operational error handling to support experiential learning. Although conceptual, the framework proposes evaluation metrics for usability, accessibility, and pedagogical effectiveness. Its main contribution is a structured model combining gamification principles with quantitative performance indicators to enable objective assessment of technical skills. To the best of the authors' knowledge, no comparable frameworks integrating SPECT simulation, gamification, and biomedical engineering metrics for competency-based training were identified in the reviewed literature.

Keywords: SPECT; Virtual reality, Gamification, Nuclear medicine education, Learning analytics, Biomedical engineering, Serious games

1. Introduction

Nuclear Medicine is a key component of modern diagnostic imaging, supporting the assessment and monitoring of disease through radiopharmaceutical techniques. Within this domain, Single Photon Emission Computed Tomography (SPECT) is widely applied in cardiology, neurology, and oncology due to its ability to produce functional three-dimensional images of physiological processes (Cherry et al., 2012; Bailey & Willowson, 2013).

The SPECT acquisition workflow requires advanced procedural competencies, including patient positioning, gamma camera calibration, selection of acquisition parameters, and identification and correction of imaging artefacts. Despite its clinical relevance, training in these procedures remains predominantly reliant on real clinical environments. These environments are often constrained by limited access to imaging systems, high operational costs, and ethical and safety restrictions associated with ionising radiation exposure (Delbeke et al., 2012).

In response to these limitations, Virtual Reality (VR) has emerged as a promising educational technology, enabling immersive, interactive, and risk-free learning environments. Evidence indicates that VR, particularly when combined with gamification strategies, can enhance engagement, motivation, and learning outcomes in healthcare education (Deterding et al., 2011; Sailer & Homner, 2020; Gasteiger et al., 2022). However, its application in Nuclear Medicine education remains underdeveloped, particularly in relation to structured simulation of SPECT acquisition workflows and the incorporation of objective performance assessment mechanisms.

The overall study is guided by the following objective: to develop and pre-validate a gamified virtual reality platform for SPECT education and training, integrating biomedical metrics for objective performance monitoring. To achieve this objective, the following specific objectives were defined:

- To analyse the current state of the art regarding the application of virtual reality and gamification in Nuclear Medicine education and training;
- To identify the technical, functional, and pedagogical requirements for platform development;
- To develop an immersive Unity-based application compatible with the Meta Quest 3 device;
- To integrate gamification elements aimed at enhancing user engagement and learning;
- To implement biomedical and quantitative metrics for performance monitoring during platform use;

- To evaluate usability, performance, and educational potential of the developed solution.

Considering the limitations of conventional SPECT training and the emerging role of Virtual Reality and gamification in healthcare education, this study addresses the following research question:

RQ1: How can a gamified virtual reality platform integrating biomedical engineering metrics support competency-based learning and objective performance assessment in SPECT education and training?

To operationalise this research question, three sub-questions were defined:

RQ1a: What technical and pedagogical requirements should be considered in the design of a VR-based SPECT training platform?

RQ1b: Which gamification mechanisms are most suitable for enhancing learner engagement during SPECT procedural training?

RQ1c: Which biomedical engineering metrics can be used to objectively assess learner performance and competency development within the simulated environment?

The main contribution of this work is the conceptual design of a VR-based gamified training framework for SPECT acquisition. This model integrates a full procedural simulation with gamification elements and quantitative performance metrics, enabling objective assessment of technical skills in a controlled, risk-free environment. In addition, the study proposes evaluation criteria for usability, accessibility, and pedagogical effectiveness, supporting future validation of the framework. Overall, this work contributes to the development of competency-based training approaches in Nuclear Medicine and extends serious games research towards high-fidelity procedural medical imaging education

2. Methodology

2.1 Research Design

This study adopts the Design Science Research (DSR) methodology because its primary objective is the design, development, and future validation of an innovative educational artefact addressing a clearly identified challenge in SPECT education and training. Design Science Research provides a systematic framework for developing technological solutions while ensuring both scientific rigour and practical relevance (Hevner et al., 2004; Peffers et al., 2007). The proposed artefact integrates immersive Virtual Reality (VR), gamification principles, Learning Analytics, and Biomedical Engineering metrics to support competency-based learning and objective performance assessment in Nuclear Medicine education. Figure 1 presents the overall architecture of the proposed framework.

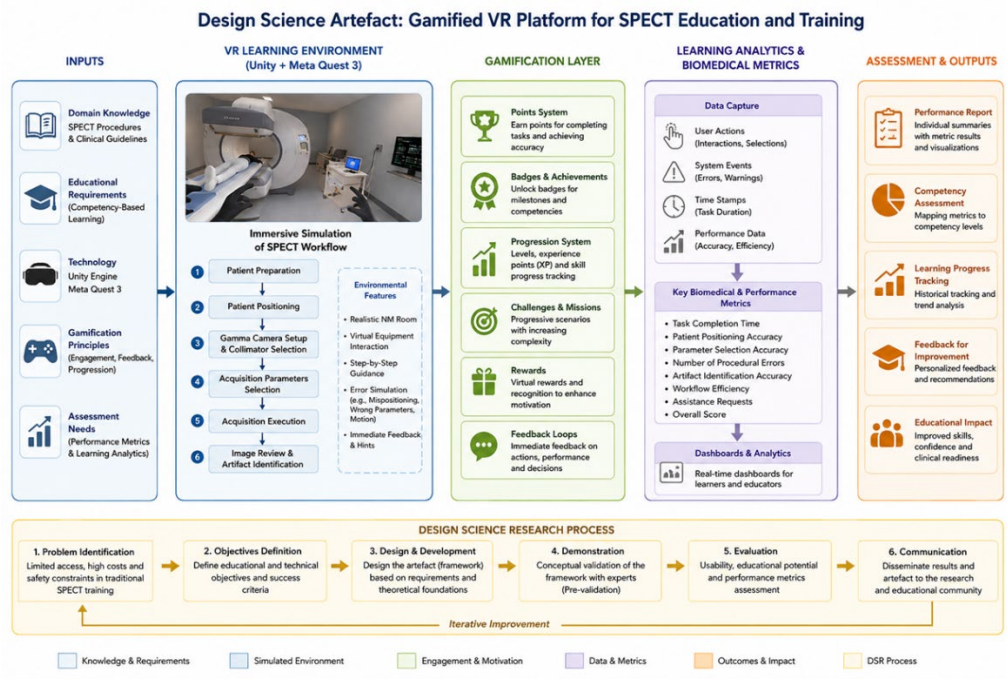


Figure 1: Overall architecture of the proposed framework

Figure 1 illustrats the relationships between the educational requirements, the virtual simulation environment, the gamification components, the Learning Analytics layer, and the expected learning outcomes. The architecture was designed to ensure alignment between pedagogical objectives, procedural simulation, and competency assessment. The proposed architecture is organised into five interconnected layers, each representing a fundamental component of the educational framework. The input layer defines the educational, technical, and pedagogical requirements derived from SPECT training needs and competency-based learning principles. These requirements guide the development of an immersive Virtual Reality environment in which learners perform the principal stages of the SPECT acquisition workflow.

To enhance learner engagement and motivation, a dedicated gamification layer incorporates progression mechanisms, challenges, achievement badges, rewards, and immediate feedback. User interactions generated throughout the simulation are subsequently processed by a Learning Analytics and Biomedical Engineering metrics layer, where quantitative indicators—including task completion time, positioning accuracy, procedural errors, workflow efficiency, and learner progression—are continuously collected and analysed.

Finally, the assessment layer transforms these indicators into competency profiles, performance reports, and personalised feedback, enabling objective monitoring of learner progression while supporting competency-based education. The proposed architecture also reflects the iterative nature of the Design Science Research methodology, allowing continuous refinement of the artefact through future implementation, testing, and validation cycles involving students, educators, and Nuclear Medicine professionals.

2.2 Structured Literature Review

The first phase of the research consisted of conducting a structured literature review to identify current evidence regarding the application of Virtual Reality, gamification, serious games, Learning Analytics, and simulation-based learning in healthcare education, with particular emphasis on Nuclear Medicine and medical imaging.

The purpose of this phase was to identify educational gaps, technological trends, and evidence-based design principles capable of informing the development of the proposed platform. In addition to establishing the current state of the art, the literature review provided the scientific foundation for defining the pedagogical approach, identifying functional requirements, and selecting appropriate performance indicators for competency assessment.

Scientific databases including PubMed, Scopus, IEEE Xplore, and ScienceDirect were consulted to ensure multidisciplinary coverage of educational technologies, serious games, immersive learning environments, and Nuclear Medicine education. The findings obtained during this phase also supported the identification of limitations associated with conventional SPECT training, reinforcing the need for immersive educational solutions capable of providing safe, repeatable, and competency-oriented learning experiences.

2.3 Requirements Analysis

The second phase focused on defining the technical, pedagogical, and functional requirements of the proposed platform. These requirements were established based on three complementary sources: **(i)** conventional SPECT acquisition procedures described in Nuclear Medicine literature and clinical guidelines, **(ii)** educational needs identified through the structured literature review, and **(iii)** competency-based learning principles.

Technical requirements addressed aspects related to hardware compatibility, software architecture, interaction mechanisms, and system performance. Pedagogical requirements focused on supporting experiential learning through progressive skill development, immediate feedback, learner autonomy, and repeated practice within a safe virtual environment. Functional requirements defined the platform capabilities, including virtual equipment interaction, procedural guidance, operational error simulation, performance monitoring, and automated feedback generation.

By combining these complementary perspectives, the proposed framework was designed to reflect current clinical practice while simultaneously addressing educational needs identified in previous research. This multidisciplinary approach ensures that both technological development and educational design remain aligned with competency-based learning objectives.

2.4 Conceptual Framework Design

The third phase focused on the conceptual design of the proposed Virtual Reality training framework. The platform was conceived to reproduce the principal stages of a conventional SPECT acquisition procedure within

an immersive and interactive learning environment, enabling learners to develop procedural competencies through repeated practice in a safe and controlled setting.

The conceptual design was guided by the requirements identified during the previous phases of the research. Technical decisions aimed to ensure compatibility with currently available immersive technologies, while pedagogical decisions were intended to support competency-based learning through experiential training, immediate feedback, and progressive skill development. Functional requirements were incorporated to reproduce authentic clinical workflows and facilitate realistic interaction with virtual medical equipment.

Unity was selected as the development environment due to its flexibility for immersive application development, support for real-time three-dimensional rendering, and compatibility with Virtual Reality devices. The Meta Quest 3 headset was selected because it provides standalone operation, intuitive user interaction, and sufficient graphical performance for immersive educational applications, making it suitable for procedural simulation in healthcare education.

The proposed virtual environment reproduces a Nuclear Medicine examination room, allowing learners to interact with a virtual Gamma Camera and associated equipment while following the principal stages of a SPECT examination. The simulated workflow includes patient preparation, patient positioning, Gamma Camera configuration, acquisition parameter selection, examination execution, image reconstruction, and image quality assessment. The environment was designed to reflect established clinical procedures while providing learners with opportunities to practise technical skills without the constraints associated with clinical equipment availability or ionising radiation exposure.

To promote active learning and clinical reasoning, the framework incorporates the simulation of common operational errors and imaging artefacts that may occur during SPECT acquisition. Learners are required to recognise these situations, identify their causes, and apply appropriate corrective actions before progressing through the training scenario. This approach encourages reflective practice while reinforcing procedural knowledge and decision-making skills.

Gamification principles were integrated throughout the conceptual framework to increase learner motivation and engagement. The proposed platform incorporates progression levels, challenge-based activities, achievement badges, performance scores, and immediate feedback mechanisms that encourage repeated practice and continuous improvement. Rather than serving solely as motivational elements, these game mechanics were designed to reinforce learning objectives and support competency development throughout the simulated training process.

The conceptual framework also incorporates a Learning Analytics layer responsible for continuously recording learner interactions during the simulation. Behavioural and procedural data generated throughout each training session provide the basis for objective performance assessment, enabling both learners and educators to monitor progression over time. The integration of Learning Analytics with Biomedical Engineering metrics represents one of the principal innovations of the proposed framework, supporting evidence-based competency assessment beyond traditional subjective evaluation methods.

Finally, the proposed framework establishes the conceptual foundation for future implementation and experimental validation. Although the present work focuses on the design of the educational artefact, the architecture has been developed to support iterative refinement through successive implementation, evaluation, and optimisation cycles, in accordance with the Design Science Research methodology.

2.5 Learning Analytics and Biomedical Engineering Metrics

Following the conceptual design of the proposed framework, a Learning Analytics layer was incorporated to enable continuous monitoring of learner performance throughout the simulated training process. This component supports the objective assessment strategy proposed within the Design Science Research methodology by transforming user interactions into measurable indicators of competency development.

Learning Analytics has emerged as a key component of technology-enhanced learning environments, enabling the collection, measurement, analysis, and reporting of learner-generated data to better understand and optimise learning processes and educational outcomes (Siemens & Long, 2011). Within game-based and immersive learning environments, Learning Analytics provides objective evidence of learner behaviour, performance, progression, and competency development, supporting data-driven educational decision-making (Banihashem et al., 2024).

In Virtual Reality training systems, user interactions generate large volumes of behavioural and procedural data that can be transformed into meaningful educational indicators. These data include task completion records, decision-making patterns, procedural errors, interaction frequencies, response times, and navigation behaviours. When systematically analysed, such indicators provide valuable insights into learner engagement, technical performance, procedural proficiency, and competency acquisition (Ifenthaler & Yau, 2020).

The proposed framework adopts a Learning Analytics approach by integrating quantitative Biomedical Engineering metrics directly into the virtual training environment. Rather than relying exclusively on subjective assessment methods, such as questionnaires or instructor observations, the platform continuously captures objective performance data during the execution of SPECT procedures. This approach is consistent with competency-based education principles, where assessment is based on demonstrated performance and measurable learning outcomes.

To support comprehensive learner evaluation, four complementary categories of performance indicators are proposed:

1. Efficiency Metrics, including task completion time and workflow duration, used to evaluate procedural fluency and operational performance.
2. Accuracy Metrics, including patient positioning accuracy, acquisition parameter selection accuracy, and imaging artefact identification accuracy, which assess the technical quality of task execution.
3. Error Metrics, including the number and severity of procedural errors, incorrect equipment configurations, and corrective interventions required during the simulation, providing objective measures of procedural competency.
4. Engagement Metrics, including challenge completion rates, progression levels, achievement badges earned, and voluntary practice frequency, which provide indicators of learner motivation, persistence, and participation throughout the training programme.

These indicators are continuously recorded by the analytics engine and aggregated into competency profiles representing different dimensions of learner performance. The resulting information can be presented through dashboards and performance reports, allowing both learners and educators to monitor progression over time, identify strengths and weaknesses, and support personalised learning pathways.

Beyond performance monitoring, the integration of Learning Analytics with Biomedical Engineering metrics represents one of the principal contributions of the proposed framework. By combining behavioural data, procedural performance, and gamification outcomes, the platform establishes an evidence-based approach to competency assessment in Nuclear Medicine education. This integration provides objective support for educational evaluation while creating opportunities for continuous refinement of both learner performance and instructional design.

2.6 Preliminary Validation Strategy

The final phase of the Design Science Research methodology focused on defining a preliminary validation strategy for the proposed Virtual Reality platform. At this stage, the objective was not to experimentally validate the educational effectiveness of the platform, but rather to establish a structured evaluation framework that will support future implementation and empirical validation.

The proposed validation strategy was designed to assess the platform from three complementary perspectives: usability, educational effectiveness, and objective competency assessment. This multidimensional approach aims to ensure that both the technological performance of the platform and its educational value can be systematically evaluated.

From a usability perspective, future studies will assess the ease of use, accessibility, and overall user experience using validated instruments such as the System Usability Scale (SUS). User satisfaction, perceived usefulness, and engagement with the gamified learning environment will also be evaluated through standardised questionnaires.

Educational effectiveness will be investigated by analysing learners' procedural knowledge, competency development, and confidence in performing SPECT acquisition procedures. Comparative studies between conventional instructional approaches and the proposed Virtual Reality platform are planned to determine whether immersive simulation and gamification contribute to improved learning outcomes.

Objective competency assessment will be supported through the integration of Learning Analytics and Biomedical Engineering metrics. During each simulation session, the platform will automatically record quantitative performance indicators, including task completion time, patient positioning accuracy, acquisition parameter selection, procedural error frequency, workflow efficiency, and imaging artefact identification accuracy. These indicators will provide objective evidence of learner progression and technical competency while complementing conventional subjective assessment methods.

Future validation studies will involve students enrolled in Biomedical Engineering and Medical Imaging and Radiotherapy programmes, together with Nuclear Medicine professionals. Participants will perform simulated SPECT procedures within the virtual environment while interaction data and performance metrics are collected. The resulting data will support the evaluation of usability, learner engagement, competency development, and the educational potential of the proposed framework.

Overall, the preliminary validation strategy establishes the methodological foundation for the future experimental evaluation of the platform. In accordance with the Design Science Research methodology, the results obtained during these validation studies will support iterative refinement of the proposed artefact, contributing to the development of an evidence-based Virtual Reality learning environment for competency-based SPECT education.

3. Proposed Training Framework

Following the methodological approach presented in the previous section, the proposed framework was translated into a conceptual Virtual Reality training environment designed to reproduce the principal stages of a conventional SPECT acquisition procedure. The platform aims to provide an immersive learning experience in which users develop procedural competencies through realistic simulation, gamification, and objective performance assessment. Figure 2 illustrates the complete user interaction workflow implemented within the proposed VR environment, highlighting the integration of procedural simulation, operational error management, gamification mechanisms, and competency assessment

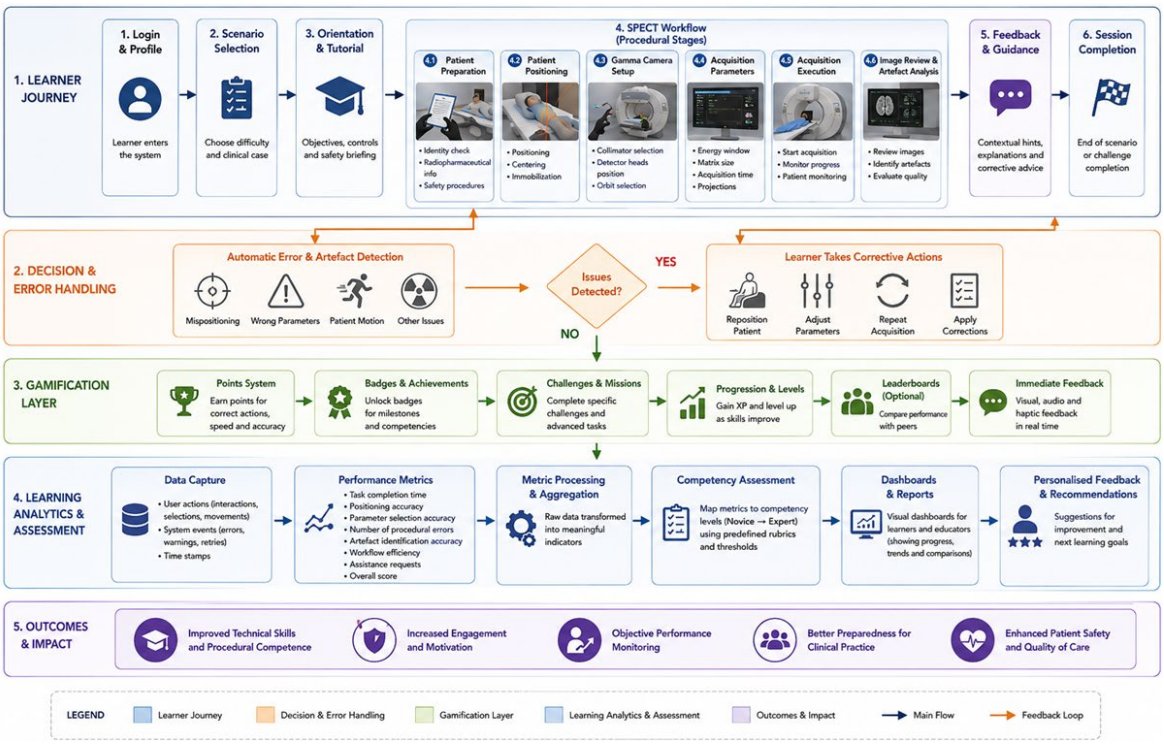


Figure 2: User Interaction Workflow within the Gamified VR SPECT Environment

3.1 Training Workflow

As illustrated in Figure 2, learners begin by selecting a training scenario and completing an introductory orientation phase that familiarises them with the virtual environment and the objectives of the examination. They then progress through the principal stages of the SPECT acquisition workflow, including patient

preparation, patient positioning, Gamma Camera configuration, acquisition parameter selection, examination execution, image reconstruction, and image quality assessment.

Throughout the simulation, learners interact directly with virtual medical equipment while following procedures that replicate conventional clinical practice. The virtual environment was designed to provide a realistic and safe learning experience, enabling repeated practice without the limitations associated with equipment availability or ionising radiation exposure.

3.2 Simulation of SPECT Procedures

To promote experiential learning and clinical reasoning, the framework incorporates the simulation of common operational errors and imaging artefacts that may occur during SPECT acquisition. These include incorrect patient positioning, inappropriate acquisition parameter selection, and patient motion during image acquisition.

Learners are required to identify these situations, determine their causes, and implement appropriate corrective actions before progressing through the training scenario. This approach reinforces procedural knowledge while encouraging decision-making and problem-solving skills within a controlled learning environment.

3.3 Gamification Strategy

Gamification principles were integrated throughout the proposed framework to increase learner engagement, motivation, and persistence during training activities. The platform incorporates progression levels, challenge-based activities, achievement badges, performance scores, and immediate feedback mechanisms that encourage continuous improvement.

These gamification elements were not included solely to increase motivation; they were intentionally designed to reinforce educational objectives, encourage repeated practice, and support the progressive development of procedural competencies required during SPECT acquisition.

3.4 Learning Analytics and Competency Assessment

During each simulation session, the Learning Analytics module continuously records learner interactions and procedural performance. Quantitative indicators—including task completion time, patient positioning accuracy, acquisition parameter selection, procedural error frequency, workflow efficiency, and imaging artefact identification accuracy—are automatically collected throughout the training process.

These data are subsequently transformed into competency profiles and personalised performance reports, enabling objective monitoring of learner progression while providing evidence-based feedback for both learners and educators. By combining immersive simulation, gamification, Learning Analytics, and Biomedical Engineering metrics within a single educational framework, the proposed platform supports competency-based learning and establishes the foundation for future implementation and experimental validation in Nuclear Medicine education.

4. Preliminary Evaluation and Expected Outcomes

The proposed framework was subjected to a preliminary conceptual evaluation based on the principles of Design Science Research (DSR). At the current stage of development, the objective was not to experimentally validate learning effectiveness, but rather to assess the coherence, feasibility, and educational relevance of the proposed artefact in addressing the challenges associated with SPECT education and training.

The conceptual evaluation considered three complementary dimensions: pedagogical alignment, technical feasibility, and assessment capability.

From a pedagogical perspective, the framework supports competency-based learning by enabling learners to perform realistic SPECT acquisition procedures within an immersive, safe, and repeatable virtual environment. The integration of progressive challenges, immediate feedback, and achievement mechanisms is consistent with established gamification principles that have been shown to enhance learner engagement and motivation (Sailer & Homner, 2020).

From a technical perspective, the proposed framework is compatible with currently available immersive technologies, including the Unity development environment and the Meta Quest 3 headset. The simulation reproduces conventional SPECT acquisition procedures while allowing interaction with virtual medical equipment and the execution of realistic clinical workflows.

A key contribution of the proposed framework is the integration of Learning Analytics and Biomedical Engineering metrics to support objective competency assessment. Unlike traditional instructional approaches that frequently depend on instructor observation, the proposed platform continuously records quantitative performance indicators, enabling evidence-based evaluation of learner progression. These indicators include task completion time, patient positioning accuracy, acquisition parameter selection accuracy, procedural error frequency, workflow efficiency, and imaging artefact identification performance.

Table 1: Preliminary evaluation dimensions and proposed validation indicators

Evaluation Dimension	Assessment Criteria	Proposed Indicators
Pedagogical Effectiveness	Support for competency development	Skill acquisition, procedural knowledge, learner confidence
User Experience	Usability and accessibility	SUS score, task completion success rate, perceived ease of use
Engagement and Motivation	Effectiveness of gamification mechanisms	Challenge completion rate, badges earned, progression levels
Technical Performance	Platform functionality and stability	System responsiveness, interaction accuracy, error occurrence
Learning Analytics	Reliability of captured data	Data completeness, metric consistency, dashboard usability
Competency Assessment	Accuracy of performance evaluation	Correlation between metrics and competency levels

Based on the proposed framework, several expected educational outcomes can be identified.

First, the immersive simulation environment is expected to increase opportunities for deliberate practice by reducing dependence on specialised clinical equipment and minimising restrictions associated with ionising radiation exposure. Second, the integration of gamification mechanisms is expected to improve learner engagement, motivation, and persistence throughout the training process. Third, the incorporation of Learning Analytics and Biomedical Engineering metrics is expected to facilitate objective competency assessment and support personalised learning pathways based on measurable learner performance.

Although empirical validation remains a future stage of this research, the preliminary conceptual evaluation suggests that the proposed framework addresses a significant educational gap in Nuclear Medicine training. By combining immersive simulation, gamification, Learning Analytics, and objective Biomedical Engineering metrics within a single educational environment, the framework establishes a structured approach to competency-based SPECT education while providing a foundation for future implementation and experimental validation.

Future work will focus on implementing the platform in Unity for the Meta Quest 3 headset and conducting experimental validation involving students from Biomedical Engineering and Medical Imaging and Radiotherapy programmes, together with Nuclear Medicine professionals. Evaluation will include usability assessment using the System Usability Scale (SUS), user experience questionnaires, engagement measures, and analysis of the quantitative performance indicators collected during simulation sessions. Comparative studies with conventional instructional approaches are also planned to investigate the educational effectiveness of the proposed Virtual Reality platform.

To support future validation studies, the following research hypotheses are proposed:

- H1: Learners using the gamified Virtual Reality platform will demonstrate higher engagement than learners receiving conventional instruction.
- H2: The proposed Biomedical Engineering metrics will provide reliable indicators of procedural competency during SPECT training.
- H3: The gamified Virtual Reality environment will be perceived as usable, educationally valuable, and supportive of competency development by both students and healthcare professionals.

5. Conclusions

This paper presented the conceptual design and preliminary validation framework of a gamified Virtual Reality platform for SPECT education and training integrating Biomedical Engineering metrics. The proposed framework

combines immersive simulation, gamification principles, Learning Analytics, and objective performance indicators within a competency-based educational approach specifically designed for Nuclear Medicine training.

By reproducing the principal stages of the SPECT acquisition workflow, the platform provides learners with opportunities to practise technical procedures in a safe, immersive, and repeatable virtual environment. The integration of quantitative performance indicators enables objective assessment of procedural competencies, complementing conventional teaching approaches that frequently rely on subjective instructor observation.

A key contribution of this work is the integration of Learning Analytics and Biomedical Engineering metrics into a gamified Virtual Reality framework for competency-based SPECT education. To the best of the authors' knowledge, no comparable educational framework combining immersive procedural simulation, gamification, objective performance assessment, and competency monitoring for SPECT training has been identified in the reviewed literature.

Although the present work represents a conceptual framework, it establishes a structured foundation for the future development of immersive educational technologies in Nuclear Medicine. The proposed architecture provides a systematic basis for implementation, educational evaluation, and iterative refinement following the principles of Design Science Research.

Future work will focus on implementing the proposed platform in Unity for the Meta Quest 3 headset, followed by experimental validation involving students from Biomedical Engineering and Medical Imaging and Radiotherapy programmes, together with Nuclear Medicine professionals. Future studies will evaluate usability, learner engagement, educational effectiveness, and competency development through the integration of Learning Analytics and Biomedical Engineering performance metrics.

Overall, the proposed framework contributes to advancing competency-based education in Nuclear Medicine while demonstrating the potential of immersive Virtual Reality technologies to support objective, evidence-based procedural training in medical imaging.

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