

Gamified Virtual Reality for SPECT Education: An Educational Innovation Framework Integrating Learning Analytics and Biomedical Engineering Metrics

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Abstract—Innovation in higher education increasingly requires more than the adoption of new technologies: it requires the redesign of learning opportunities and assessment. Nuclear Medicine is a particularly demanding context because practical training in SPECT is constrained by equipment availability, operational costs, clinical workload and radiation-protection requirements. This paper presents SPECT Explorer, a gamified immersive Virtual Reality platform designed to complement SPECT education and training, and describes the educational framework underpinning its development. The work focuses on the pedagogical principles guiding platform development,

the three knowledge gaps identified by a scoping review, the learning architecture, gamification, learning analytics, and the integration of Biomedical Engineering metrics. The platform was implemented in Unity for Meta Quest 3 and organises learning through six sequential missions covering the main SPECT workflow. Learner actions are captured and analysed through indicators such as execution time, errors, attempts, action sequence and protocol compliance, while image-related activities incorporate image quality metrics as signal-to-noise ratio, Contrast-to-Noise Ratio, contrast, spatial resolution, uniformity and artefact identification. A multidimensional pre-validation framework combines knowledge, usability, workload, behavioural and technical indicators. The main contribution extends beyond the use of VR itself and lies in an educational architecture that connects authentic procedural learning, formative feedback, Learning Analytics and domain-specific technical evidence. SPECT is used as a case because it provides a strong relationship between learner decisions, procedural consequences and measurable image-quality outcomes. The platform provides a structured foundation for future empirical evaluation of learning outcomes and competency development in SPECT training.

Keywords— SPECT; Virtual Reality; Gamification; Learning Analytics; Innovation in Education.

I. INTRODUCTION

Innovation in education is increasingly necessary when the technological environment in which students are expected to work evolve more rapidly than traditional training contexts. Higher education cannot simply add new technologies to established teaching practices; it must redesign learning experiences so that technology is used to create educational opportunities that would otherwise be difficult, costly, unsafe or impractical to provide. This is particularly relevant in health and biomedical engineering, where practical competence depends on interaction with complex equipment, procedures and decision-making under constraints. Domingues et al. (2022) argue for education capable of responding to accelerated social and technological change, while Simões and Domingues (2018) emphasise the need to reconsider education in the context of human–technology interaction. These principles motivate the present work.

Nuclear Medicine plays an important role in the diagnosis, staging and monitoring of various diseases by providing functional information about organs and tissues. However, practical training in this field faces limitations related to equipment availability, operational costs, and radiation protection requirements, restricting students' opportunities for training in clinical environments. In SPECT, students must integrate clinical information, patient preparation, detector and collimator selection, acquisition parameters, image processing and image-quality assessment. The educational challenge extends beyond access to equipment. It is the difficulty of providing repeated opportunities to practise a complete procedural workflow while maintaining safety, consistency and meaningful assessment.

Virtual Reality (VR) can complement conventional teaching by providing safe, repeatable and controlled practice. Recent evidence supports the educational potential of immersive VR while also showing that outcomes depend on instructional design, assessment strategy and implementation conditions (Zhang et al., 2025; Torosian et al., 2025). Gamification can structure progression and feedback, but its educational value depends on the pedagogical function assigned to game elements rather than on their mere presence (Aster et al., 2024). The present work therefore does not treat VR or gamification as ends in themselves. It addresses their integration into a pedagogically structured learning environment supported by

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Learning Analytics and domain-specific performance metrics.

The work presented here was developed from a dissertation whose first phase comprised a Scoping Review of immersive technologies and gamification in health education, followed by the design of the SPECT Explorer platform. The review

informed the identification of relevant knowledge gap and the design rationale underpinning platform development; the contribution of this paper is the educational and technological model resulting from that evidence and its operationalisation in a SPECT case



Fig. 1. Educational objectives and integrated components of SPECT Explorer.

The scoping review identified three related gaps. First, there is a domain-specific gap: immersive educational applications are increasingly reported in medicine and medical imaging, but applications addressing Nuclear Medicine and the complete SPECT workflow remain scarce. The scoping review identified only a small number of Nuclear Medicine applications, including an immersive hot-laboratory simulation and a VR programme for myocardial perfusion imaging (Marshall et al., 2024; Kung et al., 2026). These studies demonstrate feasibility of immersive technologies in Nuclear Medicine education, but they do not establish a comprehensive educational environment for the full SPECT workflow.

Second, there is a pedagogical integration gap. The literature includes simulation, immersive environments, serious games, game-based learning and gamification, but these approaches are heterogeneous. The relevant question is not whether a platform contains VR or game elements, but whether its technology, learning objectives, tasks, feedback and progression are coherently aligned within an instructional design framework. This distinction is consistent with recent reviews of serious games and immersive learning, which emphasise the importance of theoretical and pedagogical grounding (Aster et al., 2024; Stracke et al., 2025).

Third, there is an assessment gap. The studies mapped in the dissertation used knowledge tests, performance assessments, questionnaires, satisfaction measures, usability instruments and

qualitative approaches. Such measures are valuable but often provide evidence of outcomes after the learning activity rather than detailed information about learner behaviour during task execution."

. Recent work on VR assessment likewise identifies assessment as an emerging use rather than a mature practice (Neher et al., 2025). Learning Analytics offers a complementary route because it can capture what learners actually do during an activity, while recent higher-education research points to the need for stronger frameworks connecting emerging technologies, assessment and feedback (Sembey et al., 2024).

The SPECT case is particularly suitable for addressing these gaps. It combines a constrained clinical learning environment with a structured workflow, authentic technical decisions and measurable consequences for image formation and quality. It therefore enables the integration of four elements that are often evaluated separately:: learning activity, learner action, procedural performance and technical outcome

II. METHOD AND DESIGN BASIS

The study adopted an applied design-oriented approach centred on the development of a SPECT training platform.. The scoping review was used as a design process rather than as the main object of the paper. Evidence concerning immersive learning, gamification, evaluation methods and Nuclear Medicine applications was used to derive educational and

functional requirements.. The resulting case study focused on the design and implementation of SPECT Explorer and on the definition of a framework for preliminary validation

The platform was implemented in Unity using C# for the Meta Quest 3. Its architecture comprises distinct modules for authentication and user management, the virtual environment, simulation, gamification, learning analytics, data storage, and performance reporting . The design principle is that a learner interaction should generate an educational state and, where appropriate, an analysable data point. This is the basis for moving from a VR demonstration to an educational platform.

TABLE I. KNOWLEDGE GAPS IDENTIFIED IN THE SCOPING REVIEW AND THEIR OPERATIONALISATION IN SPECT EXPLORER.

Gap	Evidence identified	Response in SPECT Explorer
Domain-specific	Few immersive solutions address Nuclear Medicine and the complete SPECT workflow.	Dedicated immersive SPECT environment and end-to-end procedural missions.
Pedagogical integration	VR, simulation and game elements are heterogeneous and not always explicitly aligned with learning objectives.	Learning objectives, tasks, progression, feedback and gamification are integrated as one instructional structure.

Assessment	Knowledge, satisfaction, usability and perception are common; automatically captured technical evidence is less integrated.	Learning Analytics is combined with behavioural indicators and SPECT-related engineering metrics.
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SPECT Explorer was conceived as an immersive learning environment rather than as a virtual replica of a Nuclear Medicine room. The virtual environment provides the context, but learning is organised through explicit tasks and decisions. The platform includes a reception and case area, a gamma-camera acquisition area, a control room for acquisition parameters, and a processing and reconstruction area. The resulting environment represents the workflow that the student is expected to understand and execute.

The architecture is modular. Authentication and user management provide individual progression; the virtual environment provides spatial context and interaction; the simulation engine represents procedural rules; gamification manages progression and feedback; Learning Analytics captures interaction data; the database stores session information; and performance reports make the resulting evidence visible to the learner and educator. This separation is relevant educationally because it allows new procedures, missions and metrics to be introduced without redesigning the complete system.

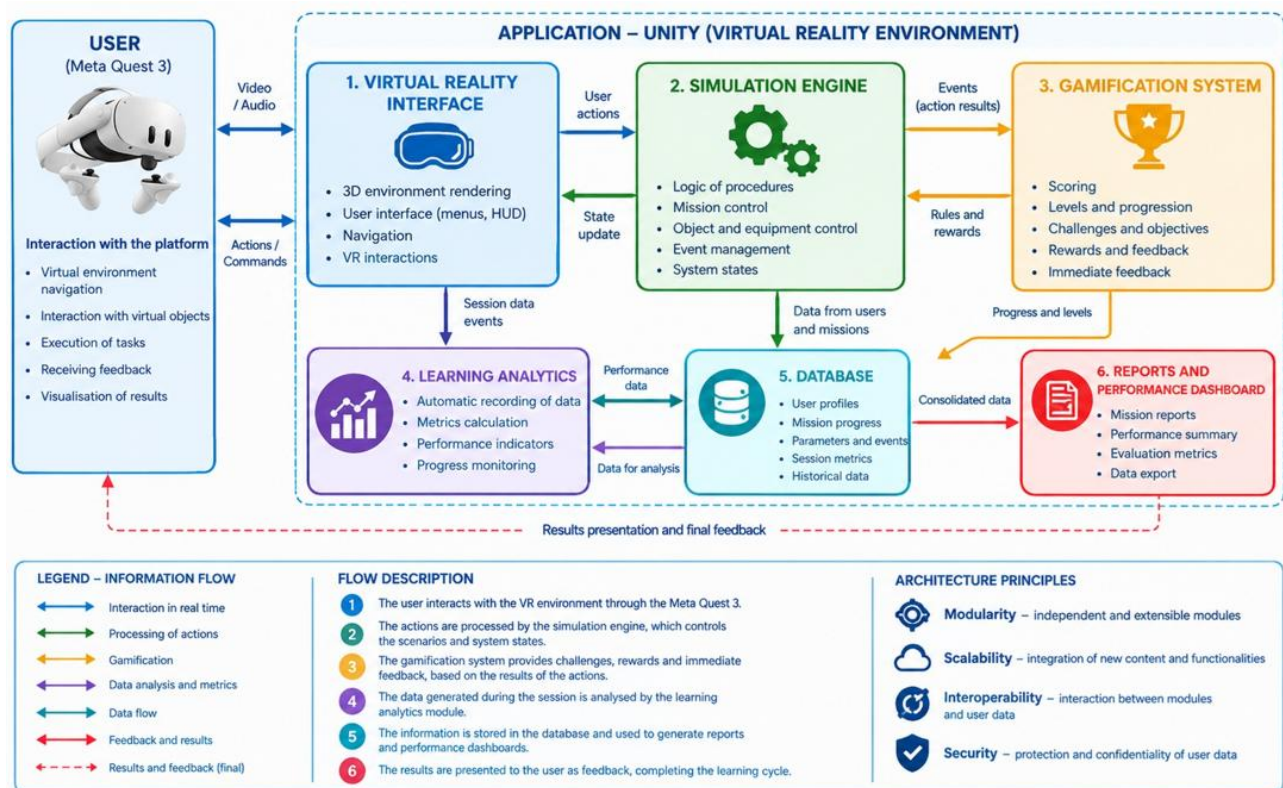


Fig. 2. Modular architecture of SPECT Explorer.

The architecture was designed around a simple educational data cycle: action, state change, measurement, feedback. For example, selecting a collimator is not treated only as an interaction with a virtual object. It is an educational decision

linked to a learning objective, a procedural state and a recordable event. The same principle applies to acquisition parameters, reconstruction options and image evaluation

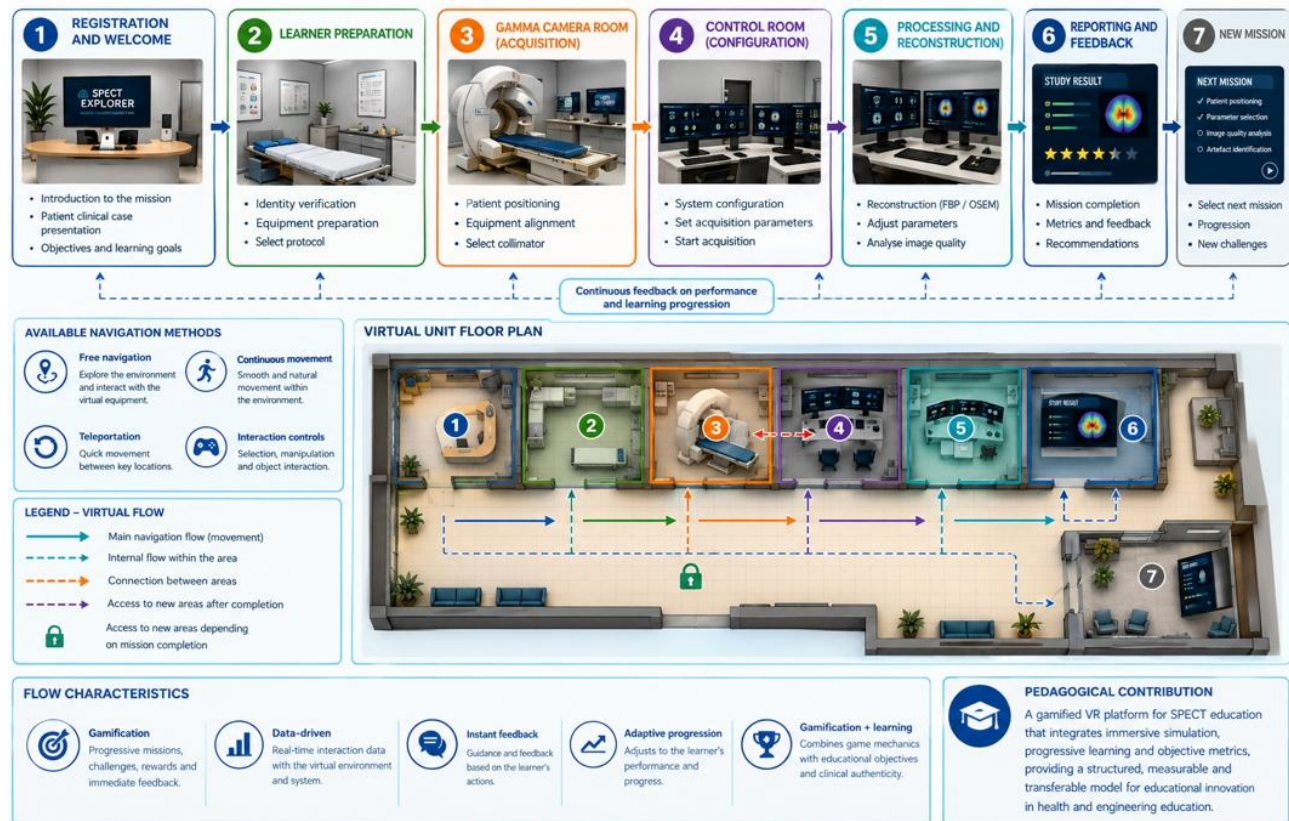


Fig. 3. Virtual Nuclear Medicine environment and workflow represented in the platform.

The resulting platform therefore has three simultaneous roles. It is a simulation environment in which the learner performs a procedure; it is a learning environment in which activities are sequenced and supported by feedback; and it is an assessment environment in which interactions can generate quantitative evidence. This integration is the central design choice of the proposed educational innovation.

The platform does not attempt to reproduce all clinical complexity. Real clinical work includes patient communication, teamwork, unexpected events, equipment-specific interfaces, institutional protocols and responsibilities that cannot be fully represented in a virtual environment. The purpose of SPECT Explorer is instead to create an intermediate learning layer between conceptual instruction and clinical practice. In this sense, its educational value should be assessed

as complementary rather than substitutive.

III. PEDAGOGICAL DESIGN, MISSIONS AND GAMIFICATION

A distinctive feature of SPECT Explorer is the integration of image-quality metrics into the learning activities related to image acquisition, processing and evaluation. These activities incorporate technical parameters associated with SPECT image quality, including signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), contrast, spatial resolution, uniformity and artefact identification. These parameters are relevant to the characterisation of image quality and system performance in Nuclear Medicine (Cherry et al., 2012; International Atomic Energy Agency [IAEA], 2014).

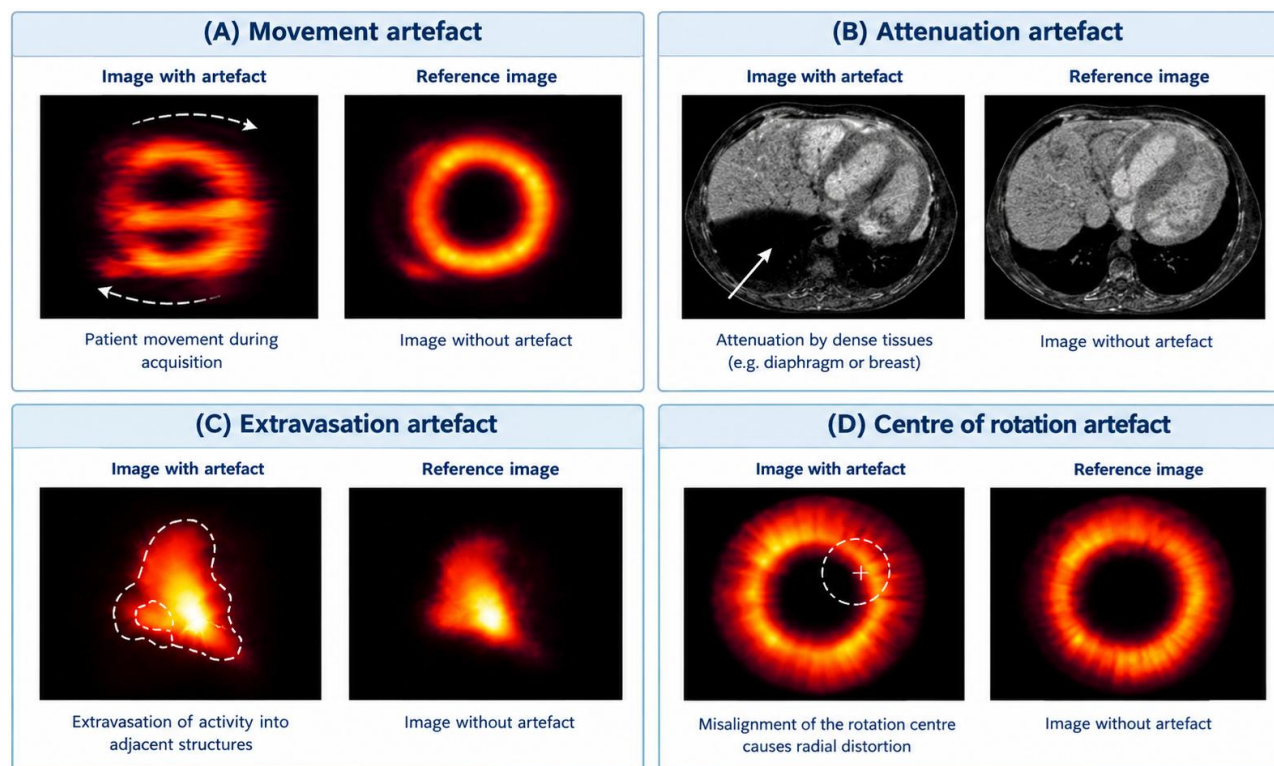


Fig. 4. Examples of artefacts observed in Nuclear Medicine: (A) movement artefact; (B) attenuation artefact; (C) extravasation artefact; and (D) centre-of-rotation artefact.

Artefact identification is particularly relevant to the educational design of SPECT Explorer because it links technical procedures and acquisition conditions with observable consequences in the reconstructed image. The examples in Figure 5 illustrate how errors or specific acquisition conditions may alter image appearance and therefore provide a basis for procedural reasoning and feedback.

However, technical image-quality metrics should not be interpreted automatically as validated measures of competence. Parameters such as SNR, CNR, contrast, spatial resolution and uniformity characterise technical properties of the image. The

fact that a learner's decision produces a particular change in one of these parameters does not, by itself, establish that the parameter is a valid measure of professional competence.

The learning experience is structured through 5 sequential missions corresponding to the main stages of a SPECT procedure: clinical case and patient preparation; gamma-camera configuration; acquisition-parameter configuration; image processing and reconstruction; and final image evaluation and feedback. Each mission combines a learning objective, a contextualised task, an expected decision or procedure, immediate feedback and automatically recorded evidence

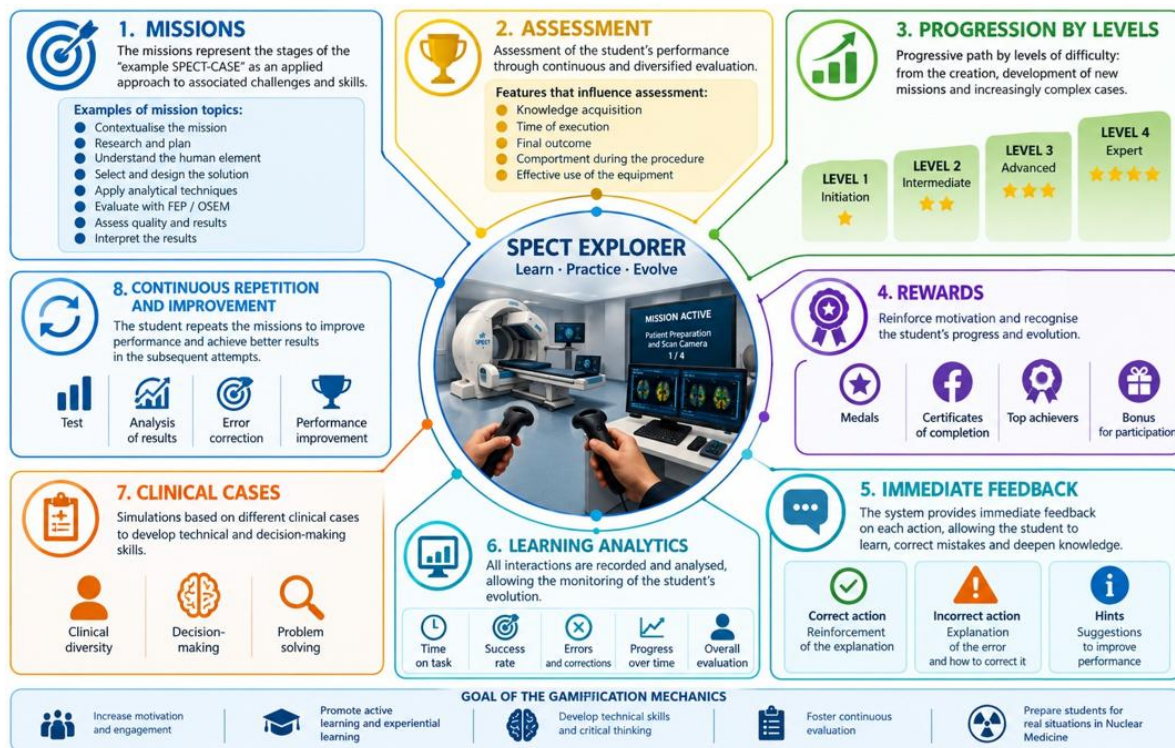


Fig. 5. Learning missions and progressive procedural structure.

The mission structure operationalises experiential learning. The student acts within a realistic context, observes the consequences of the action, receives information about errors or outcomes, and can repeat the activity. The sequence is deliberately procedural because the educational target is not isolated knowledge about SPECT but the ability to integrate knowledge into a coherent workflow.

Table 1 summarises the principal gamification elements and their intended educational functions.

TABLE II. GAMIFICATION ELEMENTS AND INTENDED PEDAGOGICAL FUNCTIONS.

Element	Pedagogical function
Sequential missions	Structure the SPECT workflow and progressive complexity.
Objectives	Clarify expected learning outcomes and task criteria.
Immediate feedback	Identify errors and support formative correction.
Repetition	Enable deliberate practice after errors or incomplete performance.
Points / experience	Represent progress and provide an explicit performance signal.
Levels / progression	Control progression and sequence access to activities.
Challenges / cases	Introduce contextualised decision-making.
Final report / debriefing	Support reflection on decisions, errors and performance.

Gamification is therefore treated as a pedagogical mechanism rather than as decoration. Objectives clarify what must be achieved; progression structures increasing complexity; challenges introduce contextualised decisions; immediate feedback supports formative correction; repetition enables practice; points and experience indicators represent progress; and the final report supports reflection. This interpretation is consistent with evidence that the educational value of game elements depends on how they are connected to learning activities and assessment (Aster et al., 2024).

Learning Analytics extends this design by preserving evidence of the learning process. Instead of recording only whether a mission was completed, the platform can capture how it was completed. Time, errors, attempts, sequence of actions, parameter selections and protocol compliance can be examined at mission and session level. Such data can support formative feedback to students and diagnostic information to educators.

The educational logic can therefore be represented as:

learning objective → authentic task → learner decision/action → procedural consequence → quantitative evidence → feedback → repetition/reflection.

This structure is relevant beyond SPECT. It provides a general pattern for designing immersive procedural learning environments in which the technology supports the learning process rather than becoming the learning objective itself.

The most distinctive component of the proposed approach is the integration of behavioural Learning Analytics with Biomedical Engineering metrics. The platform records operational indicators such as execution time, number of errors, number of attempts, task completion, action sequence, parameter selection and compliance with the expected

procedure. For image-related activities, it considers SNR, CNR, contrast, spatial resolution, uniformity and artefact identification. These parameters are grounded in the technical principles of SPECT image formation and quality assurance

(International Atomic Energy Agency, 2009, 2014; Cherry et al., 2012).



Fig. 6. Learning Analytics dashboard integrating session and performance indicators.

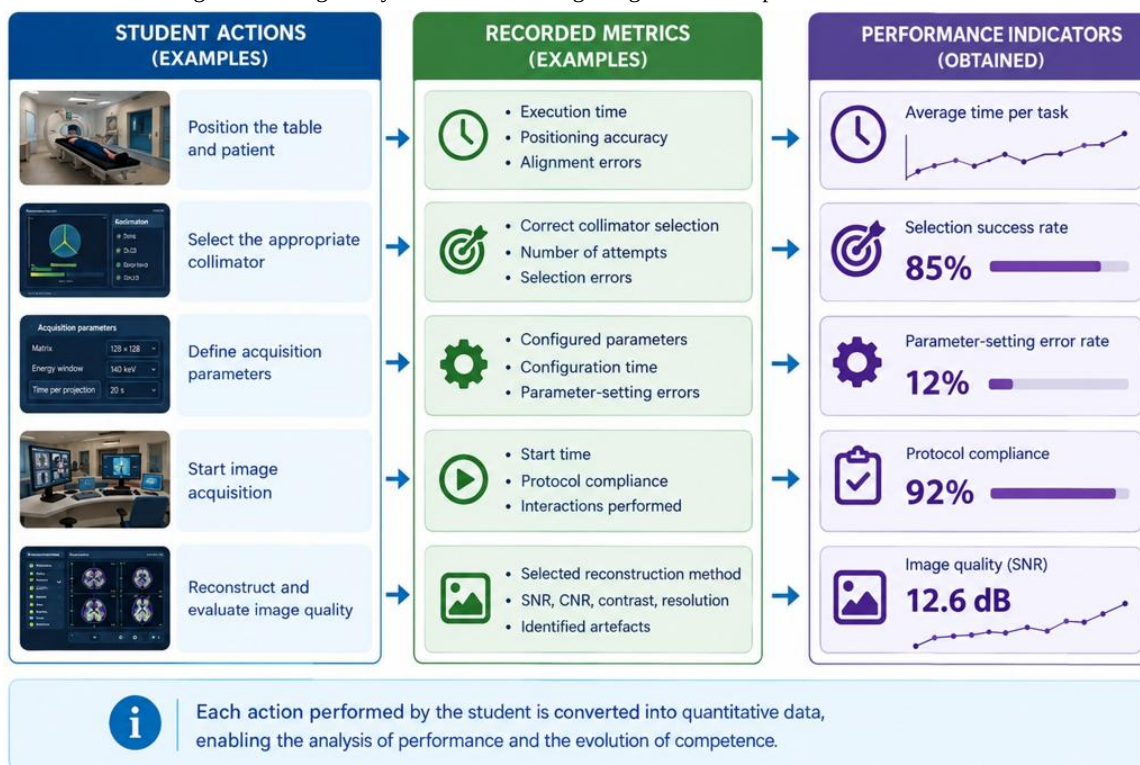


Fig. 7. Quantitative behavioural and image-quality metrics considered by the platform.

The key conceptual relation is: learner action/decision → procedural consequence → quantitative indicator → feedback.

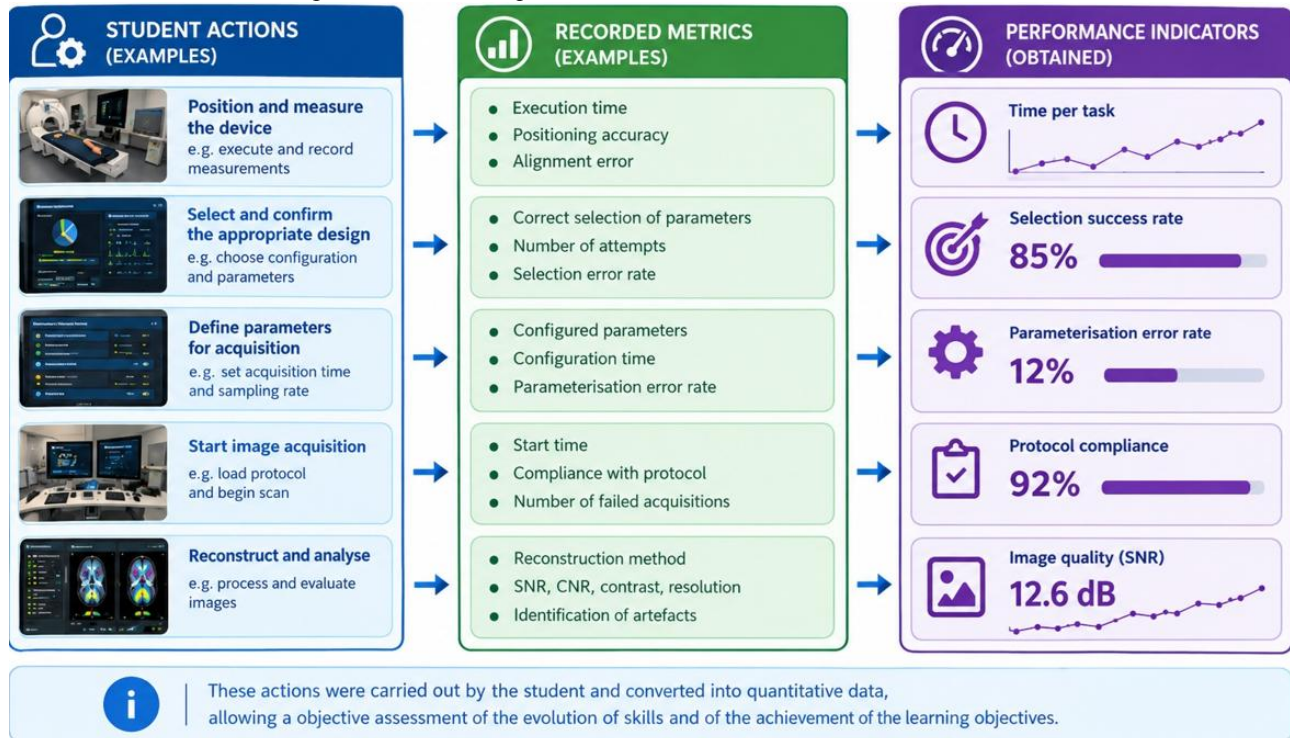


Fig. 8. Relationship between learner actions, recorded metrics and performance indicators.

This relation addresses the assessment gap identified in the scoping review. It makes the learner's interaction observable at a finer level and creates the possibility of relating decisions to technical outcomes. However, a critical distinction must be maintained. SNR, CNR, contrast, spatial resolution and uniformity are technical image-quality metrics. They are not, by themselves, validated measures of competence. Their educational validity must be established by future empirical research using expert judgement, competency criteria and appropriate comparison designs.

The pre-validation framework consequently combines complementary dimensions rather than relying on a single score. Learning is addressed through pre-test and post-test knowledge measures; usability through the System Usability Scale (Brooke, 1996); workload through NASA-TLX (Hart & Staveland, 1988); behavioural performance through automatically captured interaction data; and technical performance through procedural and image-quality indicators.

TABLE III. MULTIDIMENSIONAL PRE-VALIDATION FRAMEWORK.

Dimension	Indicators / instrument	Purpose
Learning	Pre-test / post-test	Explore changes in conceptual knowledge.
Usability	System Usability Scale (SUS)	Assess perceived usability of the platform.

Workload	NASA-TLX	Characterise perceived task workload.
Behavioural performance	Time, errors, attempts, sequence, completion, parameter selection	Characterise how the learner performs the task.
Technical performance	SNR, CNR, contrast, spatial resolution, uniformity, artefacts	Characterise technical consequences of simulated decisions.

The proposed pre-validation is exploratory. The dissertation defines a convenience sample of approximately 20–30 Biomedical Engineering students, individual sessions, familiarisation with the HMD, execution of the missions, automatic data capture and post-session questionnaires. Descriptive statistics, normality testing and paired comparisons are proposed where appropriate. The absence of a control group is deliberate at this stage because the objective is to establish feasibility, usability, data quality and preliminary relationships rather than causal effectiveness.

This distinction is important for the educational contribution. The present work demonstrates that an educational measurement architecture can be implemented. It does not yet demonstrate that the platform improves learning, that the

gamification increases motivation, or that the proposed engineering metrics validly measure competence. These are subsequent research questions.

IV. EDUCATIONAL CONTRIBUTION AND CONCLUSIONS

SPECT Explorer illustrates a form of educational innovation in which technology is introduced to address identifiable pedagogical constraints. The VR environment responds to restricted access to equipment and radiation-sensitive practice; the mission structure converts the clinical workflow into a sequence of learning activities; gamification supports progression and formative feedback; learning analytics provides the means to capture and analyse learner behaviour;

; and Biomedical Engineering metrics create a route towards objective, domain-sensitive assessment.

The advantages of SPECT as a case study are therefore methodological as well as clinical. It offers a structured workflow, multidisciplinary knowledge requirements, consequential technical decisions and measurable image-quality outcomes. This combination makes it possible to investigate links between procedural reasoning and technical performance that are difficult to establish in learning environments where outcomes are mainly conceptual or subjective.

The approach also extends the educational research agenda beyond the common question of whether students like VR. Recent evidence indicates positive potential for immersive VR in medical education, but also highlights heterogeneity, usability issues, technology-induced workload and the need for robust assessment (Zhang et al., 2025; Neher et al., 2025). The contribution here is to treat assessment as part of platform design from the beginning rather than as an evaluation added after technological development.

Three contributions emerge. First, the paper proposes an educational design model for immersive procedural learning in a high-constraint health context. Second, it presents a platform architecture linking authentic learning activities, gamification, Learning Analytics and SPECT-related engineering indicators. Third, it establishes a multidimensional pre-validation framework capable of supporting future research into learning, usability, workload, behaviour and competence.

The main limitation is that the present work reports the design and implementation of the platform and the pre-validation methodology, not completed evidence of educational effectiveness. The proposed metrics also require validation against expert performance and established competency criteria. SPECT Explorer should therefore be understood as a complementary educational tool and as a research platform for studying technology-supported learning, rather than as a replacement for clinical training.

Future work should complete the pre-validation, establish the validity and reliability of the behavioural and technical indicators, compare the platform with conventional training, examine transfer to clinical performance, and investigate adaptive learning based on learner analytics. The broader implication is that VR can support innovation in higher education most effectively when it is integrated with explicit

pedagogical design and meaningful assessment. In SPECT Explorer, the technology is not the innovation by itself; the innovation lies in using the technology to create a safer, repeatable and measurable learning process

REFERENCES

- [1] Aster, A., Laupichler, M. C., Zimmer, S., & Raupach, T. (2024). Game design elements of serious games in the education of medical and healthcare professions: A mixed-methods systematic review of underlying theories and teaching effectiveness. *Advances in Health Sciences Education*, 29, 1825–1848. <https://doi.org/10.1007/s10459-024-10327-1>
- [2] Brooke, J. (1996). SUS: A “quick and dirty” usability scale. In P. W. Jordan, B. Thomas, B. A. Weerdmeester, & I. L. McClelland (Eds.), *Usability evaluation in industry* (pp. 189–194). Taylor & Francis.
- [3] Bushberg, J. T., Seibert, J. A., Leidholdt, E. M., Jr., & Boone, J. M. (2020). *The essential physics of medical imaging* (4th ed.). Wolters Kluwer.
- [4] Cherry, S. R., Sorenson, J. A., & Phelps, M. E. (2012). *Physics in nuclear medicine* (4th ed.). Elsevier Saunders. <https://doi.org/10.1016/B978-1-4160-5198-5.00001-0>
- [5] Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining “gamification”. In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments* (pp. 9–15). Association for Computing Machinery. <https://doi.org/10.1145/2181037.2181040>
- [6] Gentry, S. V., Gauthier, A., L'Estrade Ehrstrom, B., Wortley, D., Lilienthal, A., Tudor Car, L., Dauwels-Okutsu, S., Nikolaou, C. K., Zary, N., Campbell, J., & Car, J. (2019). Serious gaming and gamification education in health professions: Systematic review. *Journal of Medical Internet Research*, 21(3), e12994. <https://doi.org/10.2196/12994>
- [7] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). North-Holland. [https://doi.org/10.1016/S0166-4115\(08\)62386-9](https://doi.org/10.1016/S0166-4115(08)62386-9)
- [8] Hong, Q. N., Fàbregues, S., Bartlett, G., Boardman, F., Cargo, M., Dagenais, P., Gagnon, M.-P., Griffiths, F., Nicolau, B., O'Cathain, A., Rousseau, M.-C., Vedel, I., & Pluye, P. (2018). The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. *Education for Information*, 34(4), 285–291. <https://doi.org/10.3233/EFI-180221>
- [9] Im, J.-E., Gu, J.-Y., Lim, E.-J., & Lee, J.-G. (2023). Virtual reality technology using a 360° video: Development and evaluation of an educational tool for intraoral radiography using the bisecting angle technique. *Virtual Reality*, 27, 3599–3612. <https://doi.org/10.1007/s10055-023-00803-1>
- [10] International Atomic Energy Agency. (2009). *Quality assurance for SPECT systems* (IAEA Human Health Series No. 6).
- [11] International Atomic Energy Agency. (2014). *Nuclear medicine physics: A handbook for teachers and students*.
- [12] Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies*, 23, 1515–1529. <https://doi.org/10.1007/s10639-017-9676-0>
- [13] Kato, K., Kon, D., Ito, T., Ichikawa, S., Ueda, K., & Kuroda, Y. (2022). Radiography education with VR using head mounted display: Proficiency evaluation by rubric method. *BMC Medical Education*, 22, 579. <https://doi.org/10.1186/s12909-022-03645-8> PubMed Central (PMC)
- [14] Knoll, G. F. (2010). *Radiation detection and measurement* (4th ed.). John Wiley & Sons.
- [15] Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice-Hall.
- [16] Kolb, D. A., Boyatzis, R. E., & Mainemelis, C. (2001). Experiential learning theory: Previous research and new directions. In R. J. Sternberg & L.-F. Zhang (Eds.), *Perspectives on thinking, learning, and cognitive styles* (pp. 227–247). Lawrence Erlbaum Associates. <https://doi.org/10.4324/9781410605986-9>
- [17] Kung, J.-Y., Chang, C.-W., Chen, Y.-W., Huang, P.-J., Tsai, S.-C., Huang, J.-L., & Chang, C.-J. (2026). Development and evaluation of a virtual reality teaching program for myocardial perfusion imaging in nuclear medicine education. *Journal of Nuclear Medicine Technology*, 54(2), 199–206. <https://doi.org/10.2967/jnmt.125.271203>
- [18] Kyaw, B. M., Saxena, N., Posadzki, P., Vseteckova, J., Nikolaou, C. K., George, P. P., Divakar, U., Masiello, I., Kononowicz, A. A., Zary, N., & Tudor Car, L. (2019). Virtual reality for health professions education: Systematic review and meta-analysis by the Digital Health Education

- Collaboration. *Journal of Medical Internet Research*, 21(1), e12959. <https://doi.org/10.2196/12959>
- [19] Larsen, J. D., Jensen, R. O., Pietersen, P. I., Jacobsen, N., Falster, C., Nielsen, A. B., Laursen, C. B., Konge, L., & Graumann, O. (2023). Education in focused lung ultrasound using gamified immersive virtual reality: A randomized controlled study. *Ultrasound in Medicine & Biology*, 49(3), 841–852. <https://doi.org/10.1016/j.ultrasmedbio.2022.11.011>
- [20] Marshall, S. K., Sirieak, N., Kamkorn, P., Keawtong, V., Hayeeabundromae, A., Noomad, N., Durawee, W., & Cheewakul, J. (2024). Nuclear medicine radiological hot laboratory simulation: A mixed-method intervention study on immersive virtual reality for sustainable education. *Applied Sciences*, 14(12), 5041. <https://doi.org/10.3390/app14125041>
- [21] Mitani, H., Honda, Y., Narita, K., Morishita, S., Kondo, S., Maeda, S., Higashibori, H., Chosa, K., Higaki, T., Kawashita, I., Hattori, M., Hasunuma, N., Saeki, I., Takahashi, S., Mihara, N., & Awai, K. (2025). Effectiveness of a virtual reality-based interventional radiology simulator for medical student education. *Japanese Journal of Radiology*, 43, 1386–1392. <https://doi.org/10.1007/s11604-025-01771-z>
- [22] Neher, A. N., Bühlmann, F., Müller, M., Berendonk, C., Sauter, T. C., & Birrenbach, T. (2025). Virtual reality for assessment in undergraduate nursing and medical education: A systematic review. *BMC Medical Education*, 25, 292. <https://doi.org/10.1186/s12909-025-06867-8>
- [23] Neyem, A., Cadile, M., Burgos-Martínez, S. A., Soto Alvarado, M., Farfán Cabello, E., Inzunza, O., Tubbs, R. S., & Ottone, N. E. (2026). Integrating virtual reality game-based learning to enhance metacognition in medical anatomy education. *Clinical Anatomy*, 39(2), 180–206. <https://doi.org/10.1002/ca.70019>
- [24] Peters, M. D. J., Godfrey, C., McInerney, P., Munn, Z., Tricco, A. C., & Khalil, H. (2020). Chapter 11: Scoping reviews (2020 version). In E. Aromataris & Z. Munn (Eds.), *JBIMES-20-12 JBI Global*. Joanna Briggs Institute. <https://doi.org/10.46658/JBIMES-20-12>
- [25] Sembey, R., Hoda, R., & Grundy, J. (2024). Emerging technologies in higher education assessment and feedback practices: A systematic literature review. *Journal of Systems and Software*, 211, 111988. <https://doi.org/10.1016/j.jss.2024.111988>
- [26] Simões, N., & Domingues, N. (2018). Humans versus machines or humans and machines? STEM and citizenship education in a post-human society. In *INTED2018 Proceedings* (pp. 8255–8263). IATED. <https://doi.org/10.21125/INTED.2018.2008>
- [27] Stern, C., Jordan, Z., & McArthur, A. (2014). Developing the review question and inclusion criteria. *American Journal of Nursing*, 114(4), 53–56. <https://doi.org/10.1097/01.NAJ.0000445689.67800.86>
- [28] Stracke, C. M., Bothe, P., Adler, S., Heller, E. S., Deuchler, J., Pomino, J., & Wölfel, M. (2025). Immersive virtual reality in higher education: A systematic review of the scientific literature. *Virtual Reality*, 29, 64. <https://doi.org/10.1007/s10055-025-01136-x>
- [29] Torosian, S., Mousakhani, V., Wehsener, S., Ramnauth, V., & Walcott-Bedeau, G. (2025). Virtual reality and preclinical medical education: A systematic review of its application and effectiveness. *Discover Education*, 4, 191. <https://doi.org/10.1007/s44217-025-00628-x>
- [30] Zhang, W., Ding, Z., Bakaev, M., Razumnikova, O., Kludacz-Alessandri, M., & Wu, J. (2025). Immersive virtual reality based on head-mounted display in medical education: A systematic review. *BMC Medical Education*, 25, 1593. <https://doi.org/10.1186/s12909-025-08154-y>