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Validity Analysis of VR-Based Particle Dynamics Module Development Using the Rasch Model

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Abstract

Physics education often encounters challenges in fostering students' conceptual understanding of particle dynamics, largely due to the abstract nature of the content and its reliance on symbolic mathematical representations, which can impede meaningful interpretation of physical phenomena. To address this issue, this study developed PADYVIR (Particle Dynamics Virtual Reality), a virtual reality–assisted learning module, and examined its validity, reliability, and practicality for use in higher education settings. The development process followed the ADDIE instructional design model, after which the module underwent expert appraisal and psychometric evaluation using the Rasch measurement model. Expert assessments involved physics education specialists and instructional design experts, who evaluated the content, construct clarity, and pedagogical appropriateness of PADYVIR and its supporting learning instruments. The research instruments employed in this study were adapted from previously validated tools reported in the literature, thereby ensuring baseline measurement validity. Rasch analysis indicated strong psychometric properties, including high person and item reliability indices, acceptable fit statistics, and evidence of unidimensionality. A limited trial with undergraduate students further demonstrated high practicality in terms of usability, attractiveness, and comprehensibility. These findings confirm that PADYVIR is a psychometrically robust and user-friendly instructional resource capable of supporting the visualization and conceptual learning of particle dynamics. Methodologically, the study contributes to the field by integrating rigorous measurement theory with immersive educational technology, offering a replicable framework for the development and evaluation of virtual reality–based learning media. Implications for instructional design and educational technology research are discussed, and directions for future effectiveness studies are proposed.

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INTRODUCTION

The rapid development of science and technology, especially with the advent of the Industrial Revolution 4.0, demands fundamental modifications in the world of education. The 21st-century curriculum emphasizes the importance of digital literacy, critical thinking skills, and problem-solving abilities (Ayu et al., 2023; Jufriadi et al., 2022). In Indonesia, the curriculum mandates that learning should not be separated from the role of technology, even in evaluation (González., 2017; Kumar & Pande, 2017; Richard., 2012). This is in line with efforts to equip students with the knowledge, skills, and attitudes necessary to adapt to rapid changes in the job market (Leopold et al., 2018). Collectively, these shifts underline the imperative for education systems to embrace

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technology-enhanced learning not merely as an add-on, but as a core component of meaningful and future-oriented pedagogy (Kompar, 2018).

Within physics education, particle dynamics is widely treated as a core component of introductory physics curricula; nevertheless, students frequently experience substantial difficulty because effective problem solving requires coordinating abstract conceptual models with formal mathematical representations (García Trillos & García Trillos, 2024; Hudha et al., 2025; Istiyono et al., 2023). Evidence from physics education research shows that when instruction foregrounds symbolic manipulation without sufficient conceptual scaffolding, learners often demonstrate a gap between procedural fluency and interpretation of physical meaning, which is a recognized barrier to robust understanding in mathematically intensive physics topics (Brundage et al., 2024; Sari et al., 2020; Scaife & Heckler, 2010). This mismatch commonly manifests as fragmented knowledge structures and persistent misconceptions, as documented in foundational mechanics learning (e.g., Newton's laws), where incorrect conceptions can endure despite conventional teaching (Defianti & Rohmi, 2021; Shanab et al., 2025). Such misconceptions are pedagogically consequential because they can constrain students' ability to transfer principles to more advanced topics that depend on coherent modelling and interpretation (Demirezen et al., 2023; Fischer & Girwidz, 2021). Traditional approaches that rely heavily on textbook exposition and lecture-centred delivery may be particularly limited in addressing these difficulties, insofar as they provide fewer opportunities for learners to actively construct meaning, test ideas, and reconcile formalism with physical intuition (Abdikadyr et al., 2025; Gunawan et al., 2021). In contrast, constructivist and student-centred designs, especially those incorporating interactive and visually supported learning experiences, are consistently positioned as better aligned with promoting conceptual understanding and sustained engagement, including for learners who may be disproportionately discouraged by abstract, formal presentations (Erceg et al., 2019; Gunawan et al., 2020; Istiyono et al., 2023). Accordingly, in the context of increasing expectations for conceptual mastery and technology-enhanced learning, there is a strong rationale for developing interactive, visually immersive instructional materials that help students connect equations to the physical phenomena they represent in particle dynamics.

Beyond conventional digital learning tools, immersive technologies such as virtual reality (VR) offer unique pedagogical affordances for physics learning. VR environments enable learners to inhabit and manipulate simulated physical worlds in three dimensions, thereby strengthening spatial reasoning, embodiment, and conceptual visualisation of otherwise abstract particle interactions. Prior research has shown that immersive learning environments can enhance engagement, reduce cognitive load associated with symbolic processing, and support deeper conceptual integration, particularly in physics topics requiring dynamic modelling (Meyer et al., 2019; Mills & Brown, 2022; Damaševičius & Sidekerskienė, 2024). In this regard, VR-assisted e-modules represent a promising development direction for supporting conceptual mastery in particle dynamics.

One promising solution is the development of electronic modules (e-modules). E-modules are non-printed teaching materials that are packaged interactively by combining text, images, audio, and video (Kim & Thayne, 2015; Meyer et al., 2019). The use of technologies such as virtual reality (VR) can further enhance the effectiveness of e-modules by allowing students to visualize abstract concepts. Studies show that learning integrated with technologies such as augmented reality (AR) can improve students' literacy skills and motivation (Damaševičius & Sidekerskienė, 2024; Mills & Brown, 2022). In addition, technologies such as three-dimensional technology have also been proven to increase student interest and enthusiasm due to their attractive appearance, ease of access to materials, and accessibility anywhere via mobile devices (Herawati & Muhtadi, 2018; Maharcika et al., 2021). Although the potential for developing technology-based modules is enormous, the validity and reliability of these learning instruments must be rigorously tested. This is to ensure that the modules are not only engaging but also effective in measuring and improving student understanding. One of the most sophisticated methods for validating instruments is the Rasch Model (Azizah & Wahyuningsih, 2021; Boone, 2016). The Rasch model can comprehensively evaluate the quality of instruments, including their internal consistency, reliability, validity, and effectiveness (Soeharto & Csapó, 2022; Tesio et al., 2024). With the Rasch Model, we can analyze the difficulty of each question item and the ability of each respondent, thereby ensuring that the developed module has an appropriate level of difficulty and provides accurate measurement results (Aryadoust et al., 2019; Tarigan et al., 2022). In this way, the development of technology-based learning modules can be grounded not only in pedagogical innovation but also in robust measurement science, thereby supporting credible conclusions regarding their educational impact.

Despite the rapid growth of technology-enhanced learning media, many development studies in physics education have focused primarily on usability, attractiveness, or learning outcomes, while paying comparatively less attention to the psychometric quality of the evaluation instruments used to measure learning effects. Several studies developing digital or immersive learning modules report expert judgement or small-scale classroom trials, yet do not conduct rigorous measurement validation such as item-level analysis, unidimensionality testing, or reliability modelling (Asrizal et al., 2021; Huda et al., 2020). As a consequence, conclusions regarding the effectiveness of these innovations may be compromised by the limited construct validity and reliability of the instruments employed. This highlights the need for development studies that integrate systematic instructional design with robust psychometric validation procedures.

Against this background, the novelty of this study lies in its integration of immersive virtual reality technology with rigorous psychometric validation using the Rasch measurement model in the context of physics module development. Whereas previous studies on digital learning media have often focused primarily on user attractiveness or descriptive validation based on classical test theory, the present study provides objective measurement evidence by disentangling item functioning and rater consistency through Rasch analysis. Furthermore, this study contributes methodologically by demonstrating how the ADDIE instructional design framework can be systematically combined with modern measurement theory to ensure both instructional quality and measurement precision in technology-enhanced physics education.

So far, research on the development of measurement instruments, such as AI literacy and literacy (Keller et al, 2023), has shown that the Rasch Model is a very effective tool (Aryadoust et al., 2019; Azizah & Wahyuningsih, 2020; Soeharto & Csapó, 2022; Tesio et al., 2024). Therefore, this study aims to adapt and apply the same approach in developing PADYVIR (Particle Dynamics Virtual Reality) modules. By designing and developing PADYVIR (Particle Dynamics Virtual Reality) modules and analyzing their validity using the Rasch Model, this study is expected to make a real contribution to efforts to improve the quality of physics learning at the higher education level. The objective of this study is to design and develop a PADYVIR (Particle Dynamics Virtual Reality) module and to examine its validity and practicality through expert evaluation and Rasch model analysis. This finding is expected to be a valuable reference for educators, researchers, and policymakers in designing innovative learning materials that are effective and adaptive to the demands of the digital age.

METHOD

Research Design and Purpose

This study employed a developmental research (Research and Development, R&D) design with a quantitative approach, guided by the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) (Branch, 2009; Prasasti & Anas, 2023; Rahmawati et al., 2023). Developmental research was selected because the primary purpose of this study was not merely to test learning outcomes, but to systematically design, validate, and evaluate an innovative learning product, namely a virtual reality (VR)–assisted particle dynamics module, ensuring its psychometric validity and practical usability in learning contexts. Accordingly, the purpose of this study was twofold: (1) To evaluate the validity and reliability of the developed module using expert judgment analysed through the Rasch model; (2) To examine the practicality and usability of the module through limited student trials.

Research Procedure

To ensure methodological transparency and facilitate replicability, the overall research procedure was structured in accordance with the ADDIE development framework. The process began with a needs analysis to identify students' conceptual difficulties in particle dynamics and the instructional requirements for VR-based visualization. This was followed by the design stage, during which learning objectives, content structure, and interaction flow were specified through the development of detailed storyboards.

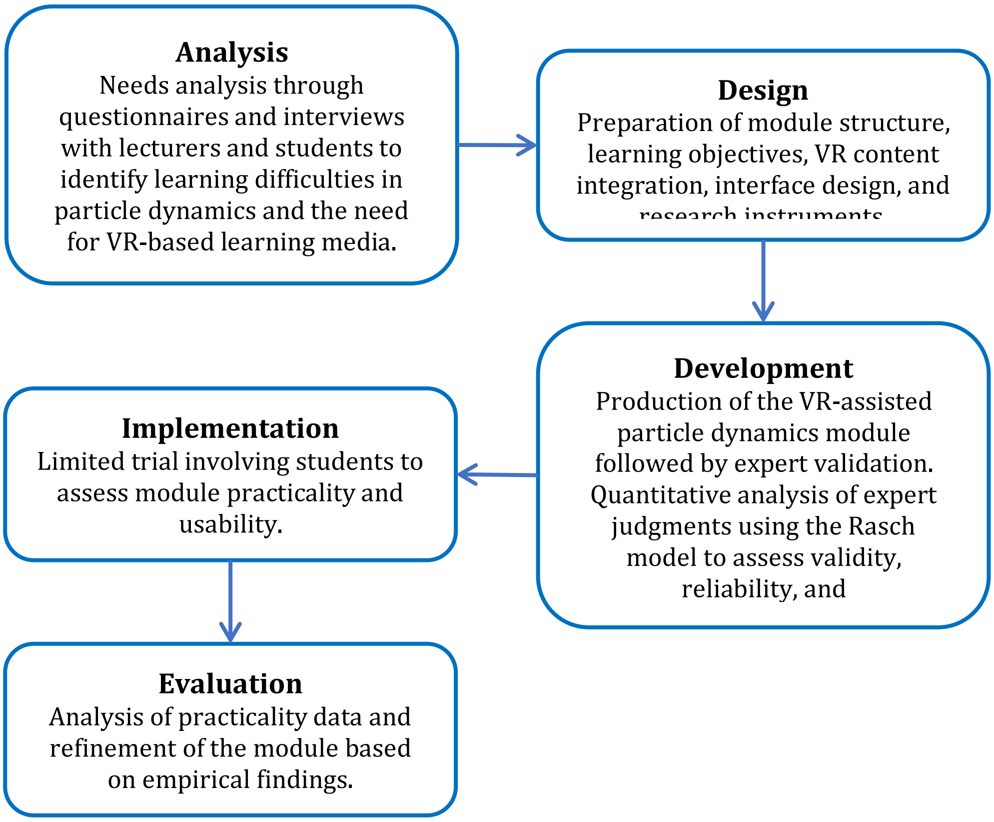

Figure 1. Research Flowchart of The PADYVIR Module Development based on the ADDIE Model (Branch, 2009)

In the development stage, the PADYVIR module was realised as a functional VR-assisted learning product integrating particle dynamics content with interactive three-dimensional visualisations. The implementation stage involved limited deployment of the module with undergraduate students, while the evaluation stage focused on expert validation and practicality assessment. Although all ADDIE stages were conducted, this article reports primarily on the development, implementation, and evaluation stages, as these directly address the validity, reliability, and practicality of the PADYVIR module.

Research Subjects

The participants in this study comprised two distinct groups. The first group consisted of six expert validators, including physics content experts, instructional media experts, and experienced educational practitioners, who evaluated the validity of the PADYVIR module. The second group included twenty undergraduate students enrolled in a physics-related programme, who participated in a limited trial aimed at assessing the practicality and usability of the module in an authentic learning context.

Research Instruments

To comprehensively address the research objectives, this study employed a set of instruments that had been previously validated in earlier empirical work (Nisa' et al., 2025). First, an expert validation instrument in the form of a module validation sheet consisting of 14 items was used to assess presentation techniques, content, and instructional feasibility, and graphic and visual design feasibility. Responses were measured using a four-point Likert scale and analysed using the Rasch measurement model to examine item fit, reliability indices, separation indices, and unidimensionality. Second, a student practicality questionnaire was administered during the implementation stage to evaluate the module's ease of use, attractiveness, and ease of understanding from the learners' perspective.

Data Analysis Techniques

Expert validation data were analysed using the Rasch measurement model, with particular attention to item fit statistics (Infit and Outfit Mean Square (MNSQ) and Z-standardized (ZSTD) values), reliability indices, separation indices, and unidimensionality criteria (Bond et al., 2021; Smith, 2003). These analyses were conducted to ensure that the validation instrument functioned reliably and measured a single underlying construct. Practicality data obtained from student questionnaires were analysed descriptively to determine overall usability and acceptance levels of the PADYVIR module (Asih et al., 2022; Sardi, 2024).

RESULTS AND DISCUSSION

Major Findings of the Study

In accordance with the ADDIE instructional design framework, this study began with the analysis stage, during which a comprehensive needs analysis was conducted to identify conceptual and instructional challenges associated with learning particle dynamics. The analysis revealed that students frequently experience difficulties in interpreting abstract concepts and relating mathematical representations to physical phenomena, thereby highlighting the need for immersive visualisation tools to support conceptual understanding. These findings informed the pedagogical scope, learning objectives, and technical features of the PADYVIR (Particle Dynamics Virtual Reality) module.

The subsequent design stage focused on translating the outcomes of the needs analysis into a structured instructional blueprint. At this stage, a detailed storyboard was developed to specify the sequence of learning activities, the integration of particle dynamics concepts with virtual reality elements, and the interaction flow between users and the virtual environment. The storyboard functioned as a conceptual and visual guide to ensure alignment between learning objectives, instructional content, and VR-based visualization strategies.

During the development stage, the storyboard was realised as a functional VR-assisted learning product. PADYVIR was developed by integrating particle dynamics content with immersive three-dimensional virtual environments that allow learners to observe and interact with simulated physical phenomena. This stage resulted in a complete instructional module that was subsequently prepared for expert validation and limited implementation. The instructional design of PADYVIR comprises several learning scenes, each targeting a core concept in particle dynamics. These scenes were developed to visualize fundamental principles such as Newton's second law, static and kinetic friction, and elastic collisions. Each scene integrates conceptual explanations with interactive visual representations, enabling learners to manipulate variables such as force, mass, and velocity and to observe their effects in real time. This design approach was intended to support conceptual integration by explicitly linking mathematical relationships with observable physical behaviour.

Validation Results of the PADYVIR Module

The validation stage aimed to evaluate the validity and reliability of the developed PADYVIR module through expert judgement, analysed using the Rasch measurement model. Before the Rasch analysis, the consistency of expert assessments was examined to ensure the reliability of the validation process. As presented in **Table 1** and **Table 2**, the Cronbach's Alpha value of 0.746 and the average-measure ICC value of 0.749 indicate good inter-rater reliability (Boone, 2016; Tennant & Conaghan, 2007), confirming that the expert judgements were sufficiently consistent for further psychometric analysis (Smith et al., 2008).

Table 1. Reliability of the Validator Team

Reliability Statistics	
Cronbach's Alpha	N of Items
.746	6

Table 2. Intraclass Correlation Coefficient

	Intraclass Correlation[b]	Sig
Single Measures	.299[a]	.000
Average Measures	.749[c]	.000

Descriptive validation results show that the module achieved high quality across all assessed aspects. Table 3 indicates that presentation techniques, presentation suitability, and graphic suitability obtained mean scores ranging from 3.75 to 3.90, all categorized as *very good* (Wang & Chen, 2005). Similarly, Table 4 demonstrates that learning objectives, instructions for use, material description, module characteristics, and physical appearance were consistently rated at a very good level, with an overall mean score of 4.65 (Mak et al., 2006). These findings suggest that the module meets established standards for instructional design, content clarity, and visual quality.

Table 3. Average Module Validation Results per Aspect

Assessment Aspects	Average Score	Category
Presentation Techniques	3.90	Very Good
Presentation Suitability	3.85	Very Good
Graphic Suitability	3.75	Very Good
Overall Average	3.82	Very Good

Table 4. Product Validation Results by Expert Team

Assessment Aspects	Average Score	Category
Learning Objectives	4.70	Very Good
Instructions for Use	4.60	Very Good
Material Description	4.55	Very Good
Module Characteristics	4.80	Very Good
Physical Appearance	4.75	Very Good
Overall Average	4.65	Very Good

To provide objective evidence of instrument quality, expert validation data were further analysed using the Rasch model. The results, summarised in Table 5, indicate high person reliability (0.94) and item reliability (0.98), exceeding the recommended threshold for educational measurement instruments. The item separation index of 3.52 confirms that the validation items were able to distinguish different levels of quality within the module (Fisher, 1993; Hagquist, 2008). In addition, Cronbach's Alpha reached 0.97, indicating excellent internal consistency. These results demonstrate that the validation instrument functioned reliably and that expert judgements were psychometrically sound (Bond et al., 2021; Pallant & Tennant, 2007). Additional Rasch fit analysis demonstrated that all items met the acceptable fit criteria, with Mean Square (MNSQ) values well within the recommended range, signifying a well-functioning scale (Hermansson et al., 2004).

Table 5. Reliability & Separation

Aspect	Average Score	Category
Person Reliability	0.94	Very Good
Item Reliability	0.98	Very Good
Item Separation	3.52	Good
Cronbach's Alpha	0.97	Very Good

Further Rasch fit analysis showed that all validation items met acceptable criteria, with Infit and Outfit Mean Square (MNSQ) values within the recommended range of 0.6–1.4 and Z-standardised (ZSTD) values within ±2. Unidimensionality analysis revealed that the raw variance explained by the measures exceeded 40%, indicating that the instrument effectively measured a single construct, namely the validity of the PADYVIR (Particle Dynamics Virtual Reality) module (Aryadoust et al., 2019; Rost, 1990). The evidence of unidimensionality is particularly important in the context of educational media validation, as it indicates that the assessment focused on a coherent quality construct rather than a mixture of unrelated criteria. This suggests that expert judgements were anchored in a shared understanding of module quality, enhancing the interpretability of the validation outcomes and supporting the use of the instrument for systematic instructional evaluation.

These fit results indicate that each validation item contributed meaningfully to measuring the intended construct, namely the instructional and visual quality of the PADYVIR module. From a pedagogical perspective, well-fitting items suggest that the evaluation instrument captured coherent aspects of module design rather than fragmented or unrelated features. This strengthens the argument that the module's quality indicators, such as clarity of presentation, conceptual alignment, and visual representation, operate as an integrated system that supports meaningful learning experiences.

Implementation and Practicality Results of The PADYVIR (Particle Dynamics Virtual Reality) Module

Following validation, the PADYVIR (Particle Dynamics Virtual Reality) module was implemented in a limited trial involving undergraduate students to examine its practicality and usability, in accordance with the stated research objectives. Before data collection, students were introduced to the module and guided through its main features, including navigation, interaction with virtual objects, and exploration of particle dynamics phenomena within the virtual environment. During this implementation phase, students actively engaged with the module as part of a structured learning activity, allowing them to experience the instructional flow and immersive visualisation provided by PADYVIR. Documentation of these implementation activities, including student interaction with the VR environment, is presented in Figure 2**,** which illustrates the real-world application of the developed module.

Figure 2. Documentation of PADYVIR (Particle Dynamics Virtual Reality) Module Implementation During the Limited Student Trial

Practicality data were subsequently collected using a student questionnaire focusing on ease of use, attractiveness, and ease of understanding. The results of this stage are presented in Table 6. As shown in Table 6, all assessed aspects achieved mean scores above 4.50 and were categorized as *very good* (Asrizal et al., 2021; Helda et al., 2024). The attractiveness of the module obtained the highest average score (4.65), followed by ease of understanding (4.60) and ease of use (4.55), resulting in an overall average score of 4.58.

Table 6. Practicality Results of the PADYVIR Module

Assessment Aspects	Average Score	Category
Attractiveness (Appearance)	4.65	Very Good
Ease of Use	4.55	Very Good
Ease of Understanding	4.60	Very Good
Overall Average	4.58	Very Good

From a learning science perspective, these practicality outcomes may be explained through cognitive and perceptual mechanisms associated with immersive environments. VR-based representations reduce the need for learners to mentally translate symbolic or two-dimensional information into spatial models, thereby lowering extraneous cognitive load and supporting more direct conceptual mapping between representation and phenomenon. The ability to manipulate variables and observe immediate system responses also aligns with principles of experiential and inquiry-based learning, in which understanding emerges through interaction and feedback rather than passive reception. These characteristics help explain why students perceived the module as easier to understand, despite its abstract nature.

Interpretation and Significance of the Findings

The validation results are significant because they demonstrate that the module is not only subjectively well-received but also objectively valid and reliable, as per modern measurement theory. High person and item reliability values, together with acceptable fit statistics, indicate that expert judgements were consistent and that the validation instrument functioned as intended. This finding is important in the context of educational technology research, where instructional products are often evaluated using descriptive methods that do not adequately account for rater bias or item functioning. By employing Rasch analysis, this study strengthens the credibility of the validation process and provides more robust evidence of module quality. Beyond confirming statistical adequacy, the Rasch findings provide substantive evidence that the PADYVIR module operates as a structured instructional system rather than merely an engaging technological artefact. The hierarchy of item difficulty and the consistency of rater functioning indicate that the module's design elements were evaluated in a stable and discriminative manner, which is essential for distinguishing between surface attractiveness and deeper instructional quality.

The findings of this study align with prior evidence suggesting that immersive and interactive technologies can strengthen learners' engagement and perceived clarity when they are required to comprehend abstract scientific concepts (Gunawan et al., 2021; Jaya et al., 2025). In technology-enhanced learning contexts, interactive multimedia environments and well-structured e-learning experiences are consistently associated with improved learner perceptions, particularly when they facilitate visualization and provide clear instructional guidance for complex content (Dahal et al., 2023; Gunawan et al., 2025). Moreover, research on extended reality systems emphasises that the educational value of VR is contingent upon credible, usable, and pedagogically coherent implementations, indicating that positive learner responses are most likely when immersive experiences are carefully designed rather than treated as novelty interventions (Cloete et al., 2021).

Importantly, the present study extends this strand of work by complementing favourable perceptions with psychometric evidence derived from Rasch model analysis, thereby offering a more rigorous account of measurement quality than is typically reported in VR-based instructional media studies (Hughes et al., 2022). Rasch analysis is widely recognized as a robust modern measurement approach for establishing instrument functioning through indices such as person and item reliability, as well as model–data fit, which strengthens the interpretability and credibility of claims based on expert or learner ratings (Bond et al., 2021). Accordingly, by embedding Rasch-based validation within the evaluation of VR instructional media, this study contributes methodologically by addressing a common limitation of descriptive validation approaches—namely, insufficient attention to item functioning and rater-related measurement error—thereby providing more defensible evidence for the quality of the module (Lee et al., 2021; Wongpakaran et al., 2020).

It should be acknowledged that high practicality ratings in early-stage implementations may be partially attributable to novelty effects, insofar as students can express heightened enthusiasm and favourable perceptions when first exposed to innovative technologies such as VR (Dewi et al., 2024). In educational technology evaluations, practicality and user-acceptance judgements are therefore often interpreted as indicators of usability and initial feasibility rather than stable evidence of pedagogical value over time, particularly when the intervention is newly introduced and learners' responses may be influenced by the perceived innovativeness of the medium (Huda et al., 2020).

The practicality results further indicate that the module is feasible for real learning contexts. High ratings for attractiveness and ease of understanding suggest that immersive VR features successfully support learners in engaging with abstract particle dynamics concepts. These findings are particularly relevant given long-standing concerns that traditional instruction struggles to bridge the gap between mathematical representations and physical meaning in physics education. From the perspective of learning sciences, the effectiveness of PADYVIR can be interpreted through theories of representational learning and cognitive processing. Physics concepts such as particle dynamics require learners to coordinate multiple forms of representation, including symbolic equations, graphical information, and spatial visualization. Traditional instruction often places heavy demands on learners' ability to mentally transform mathematical symbols into dynamic physical events, a process that can lead to cognitive overload and fragmented understanding. By contrast, immersive VR environments reduce the need for internal representational translation by externalizing abstract relationships into observable and manipulable phenomena. This alignment between symbolic input and perceptual experience helps minimize split-attention effects and supports the integration of conceptual and mathematical knowledge within coherent mental models. Consequently, the high practicality ratings reported by students may reflect not only surface-level engagement, but also the module's capacity to scaffold deeper conceptual mapping between formal representations and physical meaning.

In addition, the limited number of participants involved in an implementation stage can constrain the generalisability of findings, because results derived from small, context-specific cohorts may not transfer reliably to broader populations or varied instructional settings (Lestari et al., 2024). This methodological limitation is common in development and validation studies of learning materials, where practicality testing is primarily intended to establish implementability and acceptance as part of an iterative design cycle, before larger-scale evaluations that can substantiate learning impact (Amini & Usmeldi, 2020; Wati et al., 2020). Accordingly, although the present results indicate strong practicality, they should be interpreted as evidence of feasibility and acceptance within the sampled context rather than definitive proof of learning effectiveness, which would require more extensive samples and outcome-focused designs.

Implications of the Study

The findings of this study have important implications for physics education, instructional design, and educational technology research, as they demonstrate that PADYVIR (Particle Dynamics Virtual Reality) constitutes a psychometrically sound instructional module with strong evidence of validity and reliability derived from Rasch model analysis. These results are particularly relevant for higher education contexts in which physics instruction often emphasises mathematical formalism at the expense of conceptual interpretation, as the immersive visualisation provided by PADYVIR supports the alignment of equations with observable physical phenomena. Furthermore, the high practicality ratings reported by students indicate that VR-assisted modules can be feasibly integrated into existing instructional settings without imposing excessive cognitive or technical demands, thereby offering lecturers and curriculum designers a viable pathway for adopting immersive technologies while maintaining usability and learner acceptance. At a broader level, the study underscores the importance of rigorous validation practices in educational innovation and illustrates the methodological value of integrating the ADDIE development model with Rasch measurement theory as a replicable framework for the development and validation of high-quality digital learning media. Methodologically, this study demonstrates that immersive learning technologies can be evaluated within a rigorous measurement framework, addressing a persistent gap in educational technology research where innovation often advances more rapidly than validation practices. The combined use of ADDIE-based development and Rasch measurement modelling offers a replicable approach for future instructional design studies seeking both pedagogical innovation and measurement precision.

For researchers, the study demonstrates that integrating instructional design models such as ADDIE with modern measurement frameworks like the Rasch model provides a replicable pathway for producing not only innovative but also psychometrically defensible learning tools. For lecturers, PADYVIR illustrates how immersive visualization can be embedded within conventional curricula without replacing foundational theoretical instruction, functioning instead as a conceptual bridge between mathematical formalism and physical interpretation. For policymakers and curriculum developers, the findings suggest that investment in immersive technologies should be accompanied by systematic validation procedures to ensure that technological innovation is aligned with measurable instructional quality rather than novelty alone.

LIMITATIONS

Despite its contributions, this study has several limitations that should be considered when interpreting the findings. The number of expert validators and student participants involved in the validation and limited implementation stages was relatively small, which, although acceptable in early-stage developmental research, may restrict the generalisability of the results to broader educational contexts. In addition, the practicality evaluation was conducted over a short implementation period, meaning that students' responses may have been influenced by novelty effects associated with initial exposure to immersive virtual reality technology; consequently, the reported practicality outcomes should be interpreted as indicators of initial usability and acceptance rather than sustained pedagogical impact. Finally, although pre-test and post-test instruments were developed to support evaluation, learning effectiveness outcomes were not reported in this article, and therefore, the findings are intentionally limited to establishing the validity, reliability, and practicality of the PADYVIR module as a foundation for subsequent effectiveness research.

Future research should extend the present work by conducting large-scale experimental or quasi-experimental studies to examine the effectiveness of PADYVIR in improving students' conceptual understanding, problem-solving skills, and the reduction of misconceptions in particle dynamics, ideally through the use of control groups and longitudinal designs to assess learning gains and retention over time. In addition, further studies may investigate the adaptability of PADYVIR across different educational levels and learner profiles, such as upper secondary education or introductory physics courses for non-physics majors, as well as compare VR-assisted modules with other visualisation technologies, including augmented reality and interactive simulations, to better understand their relative pedagogical affordances. From a methodological perspective, future development research should also refine the integration of Rasch analysis in educational technology evaluation by examining item functioning across diverse instructional contexts and user groups, thereby strengthening measurement practices and supporting the development of more robust and generalisable digital learning instruments.

CONCLUSION

This study designed and developed PADYVIR (Particle Dynamics Virtual Reality) and systematically examined its validity, reliability, and practicality through expert judgement, analysed using the Rasch measurement model, and limited student trials. The findings indicate that PADYVIR meets high standards of instructional and psychometric quality, as demonstrated by strong person and item reliability indices, acceptable model–data fit, and consistent expert evaluations. In addition, results from the limited implementation phase show that the module exhibits high practicality, with students reporting positive perceptions regarding ease of use, attractiveness, and clarity of content. A key contribution of this study lies in its methodological rigour. By embedding Rasch-based validation within the ADDIE development framework, the study advances beyond descriptive evaluation approaches commonly found in educational technology research and provides a systematic, replicable model for the development and validation of immersive digital learning media in physics education. The study establishes PADYVIR as a psychometrically sound and practically viable instructional module for particle dynamics, offering a robust empirical foundation upon which subsequent effectiveness-oriented investigations may be built.

These findings indicate that the value of PADYVIR extends beyond technological novelty. The module functions as a cognitive support tool that assists learners in translating abstract symbolic representations into observable dynamic phenomena, addressing a long-standing challenge in physics education. At the same time, the integration of Rasch measurement provides objective evidence that the evaluation process meets standards of modern measurement theory, strengthening the credibility of development research in immersive learning environments. Thus, this study not only introduces an innovative instructional product but also demonstrates a rigorous methodological pathway for validating technology-enhanced learning media in higher education physics.

AUTHOR CONTRIBUTIONS

S contributed to the conceptualization of the study, supervised the overall research process, and provided critical revisions to the manuscript. KDHG was responsible for designing the study, developing the PADYVIR module, conducting data collection and analysis, and preparing the original draft of the manuscript. MNH contributed to the methodological design, performed the Rasch model analysis, interpreted the results, and assisted in revising the manuscript. All authors read and approved the final version of the manuscript.

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