Post-pandemic e-teaching: Developing the Game for Microscopic Atom Simulation (GEMAS) to enhance students' scientific conceptions of phase structures

Muhammad Zahran[1], Achmad Samsudin[1]*, Hera Novia[1], Nuzulira Janeusse Fratiwi[1], Nurdini[1], Dena Tresna Ningsih[1], Eki Nugraha[2], Hadi Nasbey[3], Mustafa Sözbilir[4]

[1]Physics Education, Universitas Pendidikan Indonesia, 229 Dr. Setiabudi St., 40154, Indonesia
[2]Computer Science Education, Universitas Pendidikan Indonesia, 229 Dr. Setiabudi St., 40154, Indonesia
[3]Physics Education, Universitas Negeri Jakarta, 11 Rawamangun Muka Raya St., 13220, Indonesia
[4]Science Education, Atatürk University, Atatürk Üniversitesi Kampüsü, 25030, Türkiye
*Corresponding author, email: achmadsamsudin@upi.edu

Article History
Received: 23 February 2025
Revised: 18 March 2025
Accepted: 30 March 2025
Published: 31 March 2025

Keywords
E-teaching; GEMAS;
MFRM;
Post-pandemic;
Students' conceptions

Abstract
This research focuses on the early development of GEMAS (Game for Microscopic Atom Simulation) as an innovative digital teaching tool designed to support instruction on phase structures in physics education. In response to the post-pandemic shift towards technology-enhanced teaching, GEMAS was developed to integrate interactive, simulation-based pedagogy that enhances conceptual visualization. The study follows the 3D model (Define, Design, and Develop) and employs Multifaceted Rasch Measurement (MRFM) for evaluation. Validation was conducted by five experts, assessing curriculum alignment, scientific accuracy, language clarity, visual arrangement, and instructional effectiveness. These dimensions align with best practices in e-teaching, ensuring accessibility, engagement, and pedagogical rigor. MRFM analysis confirms the tool's validity, with positive average scores across all indicators. The findings suggest that GEMAS is a well-designed digital resource, ready for implementation to enhance physics instruction in post-pandemic educational settings. The implications of this study extend beyond validating GEMAS as a tool; it demonstrates how immersive 3D simulations can address persistent misconceptions in physics education, particularly in post-pandemic contexts where digital engagement is critical. By bridging abstract concepts with interactive visualization, GEMAS offers a scalable model for enhancing e-teaching practices and fostering deeper conceptual understanding among students.

How to cite: Zahran, M., Samsudin, A., Novia, H., Fratiwi, N. J., Nurdini, N., Ningsih, D. T., Nugraha, E., Nasbey, H., & Sözbilir, M. (2025). Post-pandemic e-teaching: Developing the Game for Microscopic Atom Simulation (GEMAS) to enhance students' scientific conceptions of phase structures. *Journal of Environment and Sustainability Education*, *3*(1), 115–126. https://doi.org/10.62672/joease.v3i1.55

1. Introduction

Physics education at various levels of formal education aims to help students understand the concepts, principles, and laws governing physical phenomena in everyday life. However, misconceptions often occur among students regarding several concepts, such as fluids (Irwansyah et al., 2018), momentum and impulse (Adimayuda et al., 2021; Kaniawati et al., 2021), simple harmonic motion (Nurhasanah et al., 2022; Tumanggor et al., 2020), the concept of light (Aminudin et al., 2019; Haryadi & Pujiastuti, 2020; Samsudin, 2023; Umar et al., 2021), and the concept of heat (Febrianti et al., 2019; Haryono et al., 2021; Nurul et al., 2016; Suhandi et al., 2020; Widiasih et al., 2023; Wulandari & Prihandono, 2018). For instance, in the concept of heat, students often have significant misconceptions that require a more effective instructional approach.

The concept of heat is a fundamental concept in physics that supports the development of black body radiation concepts, which then form the foundation for quantum mechanics. Research by (Nurul et al., 2016) found that 35% of 70 students had misconceptions in the sub-concept of phase changes, with similar results found by (Wulandari & Prihandono, 2018), where 44% of 34 students experienced misconceptions regarding the relationship between heat and phase changes. The study by (Febrianti et al., 2019) showed that 53% of 64 research subjects experienced misconceptions on the concept of phase changes. These misconceptions can be caused by various factors, such as ineffective teaching methods, overly abstract material, and a lack of experiments that allow students to directly observe how physics concepts apply in real life (Irwansyah et al., 2018; Kaniawati et al., 2021; Ma'ruf et al., 2021; Pratama et al., 2023; Soeharto et al., 2019; Tumanggor et al., 2020). Addressing these misconceptions requires proper conceptual remediation.

doi: 10.62672/joease.v3i1.55
© 20xx The Authors
This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License
ISSN: 3025-0714

1.1. Post-Pandemic E-Teaching

The COVID-19 pandemic catalyzed a rapid transformation in educational practices, accelerating the adoption of digital learning tools. In the post-pandemic era, educators increasingly integrate technology into physics instruction, employing e-teaching methods such as instructional videos computer simulations, augmented reality, virtual reality and educational games to enhance conceptual understanding (Adimayuda et al., 2021; Aminudin et al., 2019; Fratiwi et al., 2020; Kaniawati et al., 2021; Laurenty et al., 2021; Nurhasanah et al., 2022; Samsudin, 2023). Using interactive and visual learning media can provide a more engaging and enjoyable learning experience, thereby helping to reduce existing misconceptions.

Interactive learning through educational games is an effective approach to enhancing student engagement and addressing misconceptions in physics (Amalia et al., 2024; Cardinot & Fairfield, 2019; Li et al., 2024). These games provide concrete visualizations of complex concepts, making learning more engaging and effective (Candrawati et al., 2024; Foster et al., 2006; Haryadi & Pujiastuti, 2020; Yun et al., 2008). Through the interactivity offered by games, students can explore physics concepts in a more enjoyable way, which can help reduce misconceptions (Chaudhry et al., 2021). By integrating the Conceptual Change Model, which facilitates misconception correction through discussion, experimentation, and simulation (Agiande et al., 2015). educational games can further improve conceptual understanding.

The abrupt shift to remote learning during the pandemic exposed limitations in traditional methods for teaching abstract concepts like phase structures. Existing 2D simulations and static videos lack the interactivity needed to correct misconceptions effectively, creating an urgent demand for tools like GEMAS that leverage immersive 3D environments to replicate hands-on learning experiences virtually.

1.2. Game for Microscopic Atom Simulation (GEMAS)

Research shows that interactive educational games can be an effective solution in overcoming physics misconceptions. Research conducted by Belova & Zowada (2020) showed significant changes in students' understanding, with the average misconception score dropping from 7.6 to 6.8 after learning using educational games. Another study by Chaudhry et al. (2021) compared the use of learning media in the form of digital games with computer simulations, showing that the change in misconceptions was greater in games (20%) compared to computer simulations (16%). In addition to being able to reduce misconceptions, educational games have also been shown to increase students' interest and involvement in the learning process (Amalia et al., 2024; Cardinot & Fairfield, 2019; Li et al., 2024). Educational games also provide concrete visualizations of concepts that are difficult to understand (Candrawati et al., 2024; Foster et al., 2006; Haryadi & Pujiastuti, 2020; Rino et al., 2019; Yun et al., 2008).

While prior studies (e.g., Rino et al., 2019; Chaudhry et al., 2021) utilized 2D simulations or limited interactivity, their tools lacked the freedom for students to explore molecular behavior in three dimensions. For instance, Rino et al. (2019) employed 2D simulations with phase changes displayed through videos, while Chaudhry et al. (2021) integrated a first-person shooter interface but restricted user interaction to predefined actions. These approaches, though effective in reducing misconceptions compared to traditional methods, failed to provide open-ended exploration of atomic dynamics. GEMAS addresses this gap by offering an open-ended 3D environment where users manipulate atoms directly, enabling deeper engagement with concepts like latent heat and particle dynamics—features absent in earlier models. By allowing students to interactively observe molecular arrangements and energy transfer in real-time, GEMAS bridges the limitations of prior tools and fosters a more robust conceptual understanding of phase structures.

This study aims to (1) develop a validated 3D simulation tool (GEMAS) targeting phase structure misconceptions, (2) evaluate its scientific and pedagogical validity using Rasch measurement, and (3) establish its potential as a post-pandemic e-teaching resource. The problem centers on persistent misconceptions in phase changes (e.g., 35–53% error rates in prior studies) and the inadequacy of existing digital tools to address them. To bridge this gap, GEMAS introduces a novel approach by offering students and teachers an open-ended 3D environment where users manipulate atoms directly, enabling immersive exploration of molecular behavior at the atomic scale. By integrating interactive simulations of phase structures (solid, liquid, gas), the game allows students to observe energy transfer and particle dynamics in real-time, addressing abstract concepts through accurate visualization. This design not only enhances engagement but also supports educators with an innovative tool to strengthen conceptual understanding.

2. Method

This section details the methodology used to validate the GEMAS to enhance students' conceptions on phase structure. It includes research design, sampling, instrumentation, and data analysis using MFRM.

2.1. Research Design

This study adopts the 3D design model (Define, Design, Develop) as the foundational framework for developing GEMAS (Game for Microscopic Atom Simulation). Unlike comprehensive frameworks such as ADDIE, the 3D model prioritizes iterative validation over immediate implementation, aligning with the study's goal of refining and rigorously evaluating GEMAS before large-scale deployment (Samsudin et al., 2023). This approach ensures scientific accuracy, pedagogical coherence, and usability while systematically addressing potential limitations through expert feedback and iterative enhancements.

Complementing the 3D model, Multifaceted Rasch Measurement (MFRM) was selected to evaluate GEMAS's validity. MFRM's ability to account for multifaceted variables—such as rater bias, item difficulty, and tool quality—provides robust metrics for assessing alignment with educational standards. As illustrated in Figure 1 (GEMAS Development Process), this methodological synergy creates a structured development process that balances technical rigor with instructional effectiveness. By deferring large-scale implementation to future research, this study emphasizes the development of a validated, accessible, and engaging digital learning tool that enhances students' conceptual understanding of microscopic phase structures.

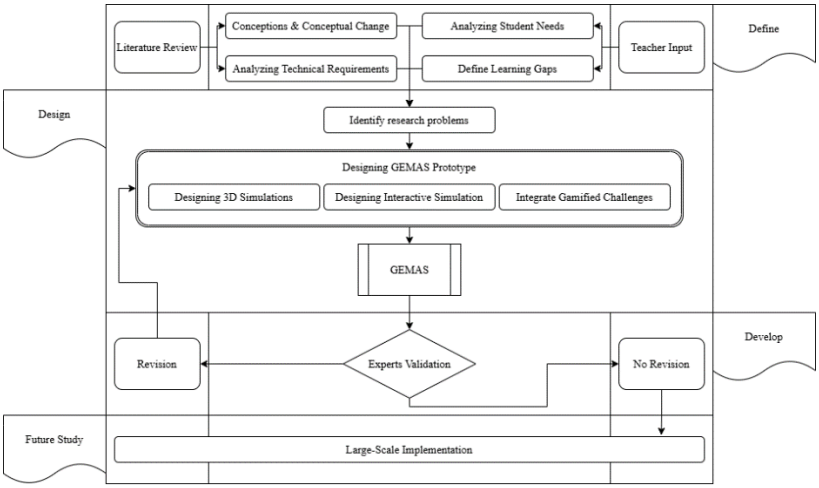

Figure 1. GEMAS Development Process

The Define stage involves a detailed analysis of students' needs to effectively understand complex phase structure concepts. In the post-pandemic era, where digital learning has become an integral part of education, it is crucial to identify how e-teaching can support conceptual understanding in science. To achieve this, existing research on common misconceptions and learning challenges related to phase structure is reviewed. Additionally, input from experienced teachers is gathered to better understand the sensory and cognitive needs of students in both traditional and digital learning environments. These insights form the foundation for GEMAS, ensuring it addresses specific learning gaps and remains accessible to students with diverse learning needs, particularly in online and blended learning settings.

In the Design stage, GEMAS is developed as a digital learning tool tailored for interactive e-teaching in science education. Given the growing reliance on virtual platforms, this phase focuses on constructing interactive game models that integrate 3D simulations, interactive simulations, and gamified challenges to enhance student engagement in remote and in-person settings. User-friendly features are also prioritized to ensure the tool's adaptability for students, supporting both independent learning and teacher-guided instruction.

The Develop stage focuses on refining GEMAS through expert validation. Experts in physics education and game technology assess the tool for scientific accuracy, accessibility, ease of use, and engagement potential in digital and hybrid learning environments. This feedback is analyzed using the Many-Facet Rasch Model (MFRM) to evaluate strengths and identify areas for improvement. Given the shift towards e-learning and blended learning models, GEMAS is designed to complement these approaches by ensuring accessibility across various devices and learning contexts. Based on expert evaluations, necessary revisions are made to enhance GEMAS's content, functionality, and inclusivity, ensuring it meets high educational standards while aligning with modern e-teaching practices.

2.2. Sampling

In this study, eight experts specializing in physics education and educational technology participated in the validation of GEMAS as a Game-based learning media. Each expert was provided with a structured validation sheet containing specific indicators, carefully designed to evaluate GEMAS across multiple dimensions crucial to

inclusive science learning. These indicators included aspects such as visual design, functional capabilities, accessibility features, usability, and instructional alignment with phase structure concepts. The experts conducted their evaluations by systematically reviewing each indicator, focusing on how well GEMAS's features and interface design support an interactive and engaging learning experience for diverse student populations. Their assessments provided insights into the appropriateness of GEMAS for enhancing students' conceptions of the phase structure, ensuring that the learning media not only met educational standards but also offered an inclusive, adaptable environment for all learners.

2.3. Instrumentation

The primary instrument utilized in this research is a structured validation sheet, designed to assess GEMAS's alignment with curriculum standards, scientific accuracy, linguistic clarity, layout quality, and instructional effectiveness. These key validation aspects are divided into 18 specific indicators, allowing experts to systematically evaluate GEMAS's effectiveness as an inclusive learning medium. The Content Indicators focus on curriculum alignment and the accuracy of scientific information related to phase structures. The Construct Indicators assess linguistic clarity, visual design, and instructional guidance. Together, these indicators provide a comprehensive framework to determine the validity of GEMAS. Additionally, we also provide students with a set of conceptual questions to assess their understanding of phase structures before and after using GEMAS (see Figure 2). Since no standardized assessment has been given yet, these questions are specifically designed to identify misconceptions, measure conceptual change, and evaluate the effectiveness of the game-based learning approach.

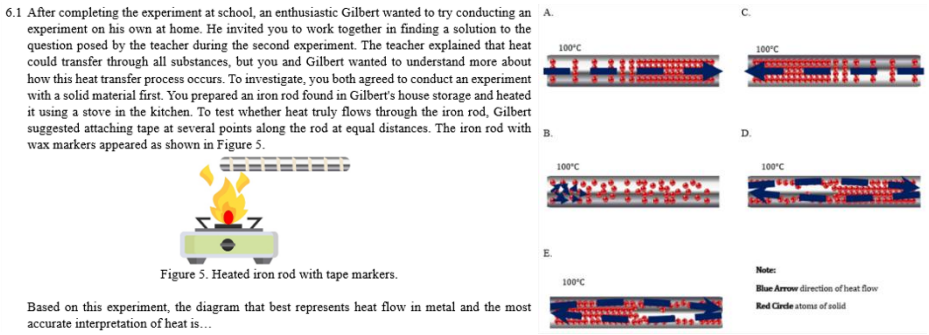

Figure 2. Example of a Conceptual Question

2.4. Analysis

Many-facet Rasch Measurement (MFRM) model, as outlined by (Eckes, 2019), was employed to evaluate the experts' validation of GEMAS. This model is well-suited for handling multifaceted evaluations, allowing for detailed analysis across multiple dimensions of the validation sheet, such as content accuracy, instructional design, and suitability for special education needs.

MFRM was implemented using Minifac software, which facilitated a structured analysis of expert ratings. The software output included key statistical measures such as logit values, which quantified the difficulty level of meeting each validation criterion, and fit statistics, which assessed the consistency of expert judgments. These measures were crucial for evaluating both the validity and reliability of the expert assessments.

To ensure data validity, we examined whether expert ratings aligned with the expected model fit. Indicators with acceptable fit values confirmed that the ratings were coherent and reflected genuine assessment patterns, whereas misfitting indicators suggested potential inconsistencies requiring further investigation. Reliability was assessed through rater consistency measures, which helped determine whether experts applied evaluation criteria consistently. The analysis also identified any biases based on expert background or specific validation criteria, further strengthening the robustness of the evaluation.

By integrating these analytical techniques, the study ensured that the validation process provided credible evidence of GEMAS's effectiveness as an inclusive science learning tool. The rigorous assessment of validity and reliability reinforced the confidence in the evaluation outcomes, supporting the model's applicability in educational settings.

3. Results and Discussion

3.1. Define

The Define stage aimed to identify and address students' misconceptions about phase structure, focusing on sub-concepts such as phase changes, the relationship between heat and phase transitions, and molecular

behavior during these processes. A review of existing literature highlighted critical gaps in understanding, which can hinder the development of accurate mental models of phase structure. These findings are supported by studies such as (Nurul et al., 2016), (Wulandari & Prihandono, 2018), and (Febrianti et al., 2019), which document pervasive misconceptions among students. For example, 35% of 70 students misunderstood phase changes, struggling to grasp the conditions under which substances transition between solid, liquid, and gas. Similarly, 44% of 34 students exhibited confusion about the interplay between heat and phase changes, often believing that temperature always increases during a phase transition or misunderstanding the role of latent heat. Additionally, 53% of 64 research subjects showed misconceptions about the molecular behavior during phase changes, such as assuming particles grow or shrink in size rather than change their spatial arrangement or energy levels.

These misconceptions shaped the design structure and interactive features of GEMAS (Game for Microscopic Atom Simulation). The game incorporates key characteristics to directly address these misunderstandings, offering immersive visualizations and interactive elements. For instance, GEMAS provides real-time simulations of particle behavior during phase changes, emphasizing energy transfer, temperature plateaus, and the rearrangement of molecules. To clarify the relationship between heat and phase transitions, the game includes scenarios that illustrate latent heat, such as melting ice and boiling water, while ensuring players understand that temperature remains constant during these processes. Furthermore, GEMAS integrates gamified challenges where players predict or manipulate conditions to observe specific phase transitions, reinforcing their understanding through active experimentation. By aligning the game's structure with these targeted misconceptions, GEMAS aims to reshape students' conceptions of phase structure, providing an engaging and effective learning experience.

3.2. Design

GEMAS is a physics educational game specifically designed in 3D to provide sophisticated simulations of phase structure. The educational game in this present study was created with the help of Unity Software. The development of GEMAS follows a structured design, beginning with the Home Scene (Figure 3), where users can start or exit the game. To ensure effective gameplay, GEMAS includes a Guidance Section, consisting of the First Guidance Scene (Figure 4) and Second Guidance Scene (Figure 5), which introduce players to the game controls and objectives.

The Main Scene (Figure 6) serves as the central hub, allowing players to navigate between different phases of matter. The game features interactive environments for each phase, starting with the Solid Scene (Figure 7), where users can explore molecular arrangements in the solid state. The Solid Simulation Scene (Figure 8) provides a dynamic visualization of solid particles' behavior.

Similarly, the Liquid Scene (Figure 9) allows users to engage with liquid-state molecules, which are further demonstrated in the Liquid Simulation Scene (Figure 10), where particle movement becomes more dynamic. The final phase, the Gas Scene (Figure 11), introduces the gaseous state, followed by the Gas Simulation Scene (Figure 12), illustrating the highly energetic motion of gas particles.

Through these structured phases and simulations, GEMAS provides an interactive and immersive approach to understanding phase structures, enhancing conceptual learning through visualization and engagement.



Figure 3. Home Scene of GEMAS



Figure 4. First Guidance Scene



Figure 5. Second Guidance Scene



Figure 6. Main Scene



Figure 7. Solid Scene

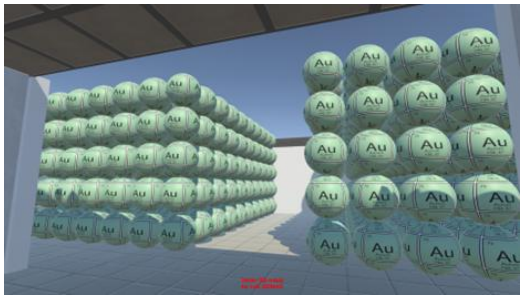

Figure 8. Solid Simulation Scene



Figure 9. Liquid Scene

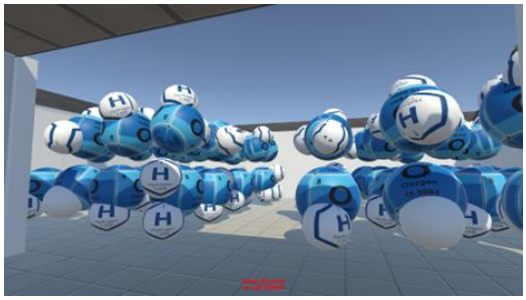

Figure 10. Liquid Simulation Scene

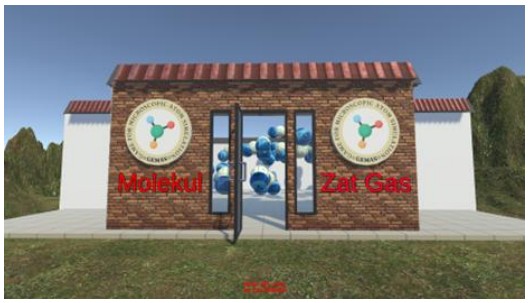

Figure 11. Gas Scene

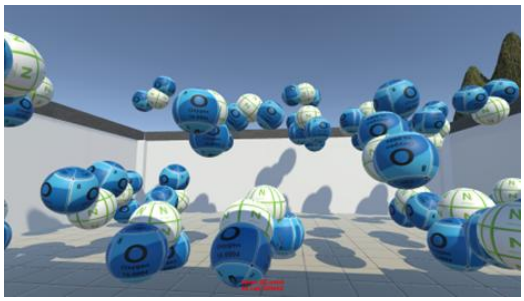

Figure 12. Gas Simulation Scene

GEMAS's 3D design (Figures 3–12) leverages Cognitive Load Theory (Sweller, 1988), which emphasizes reducing extraneous mental effort through intuitive interfaces. The phased simulations (solid → liquid → gas) scaffold learning by isolating variables (e.g., particle motion), a strategy validated in game-based environments (Cardinot & Fairfield, 2019). For example, the Gas Simulation Scene (Figure 12) visualizes chaotic molecular motion, a concept where students often oversimplify as linear expansion (Nurul et al., 2016). By contrast, GEMAS's interactive controls allow users to manipulate pressure and temperature, observing real-time particle collisions—a feature absent in prior tools (Chaudhry et al., 2021). The design also aligns with Constructivist Learning Theory (Bruner, 1966), where knowledge is actively built through exploration. This is particularly vital in hybrid classrooms, where engagement hinges on tools that replicate hands-on experimentation (Li et al., 2024).

3.3. Develop

The validation of GEMAS, conducted using Facets software, is categorized into content validity and construct validity, as illustrated in Figure 13. Content validity ensures that GEMAS effectively engages students at a cognitive level, presents scientific conceptions in a structured manner, follows a systematic approach, and

maintains scientific accuracy. Meanwhile, construct validity focuses on how easily the game can be understood through linguistic elements, its overall user-friendliness, the clarity of the simulation and instructional manual, and its ability to translate abstract scientific concepts into concrete understanding.

These validation aspects align closely with modern e-teaching principles, which emphasize the importance of interactive learning environments in improving conceptual understanding. The role of e-teaching in science education is crucial, as it provides students with dynamic visualizations and hands-on virtual experiments that traditional methods often lack. By integrating scientifically accurate content with engaging and intuitive design, GEMAS exemplifies how digital simulations can bridge the gap between abstract theories and practical comprehension.

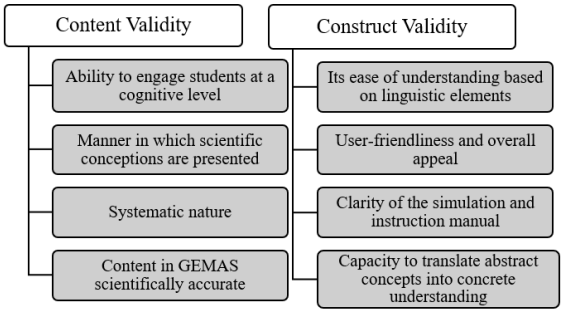

Figure 13. Framework for Evaluating GEMAS

Furthermore, user-friendliness and linguistic clarity are key factors in ensuring that students of varying backgrounds can navigate and benefit from the platform. The incorporation of instructional manuals and guided simulations aligns with constructivist learning theories, which suggest that students learn best when they actively construct knowledge rather than passively receiving information. As digital learning continues to evolve, platforms like GEMAS play a vital role in enhancing inquiry-based learning and making complex scientific concepts more accessible through engaging and interactive e-teaching methodologies.

3.4. Content Validity

The GEMAS content validity analysis, based on the Wright Map generated through the FACETS software (see Figure 14), confirms that GEMAS is a valid educational tool for teaching phase structures and their scientific concepts. The analysis highlights the evaluation of key indicators such as systematic design, curriculum alignment, and cognitive appropriateness, alongside the core content areas of solid, liquid, and gas phases within the game's simulation.

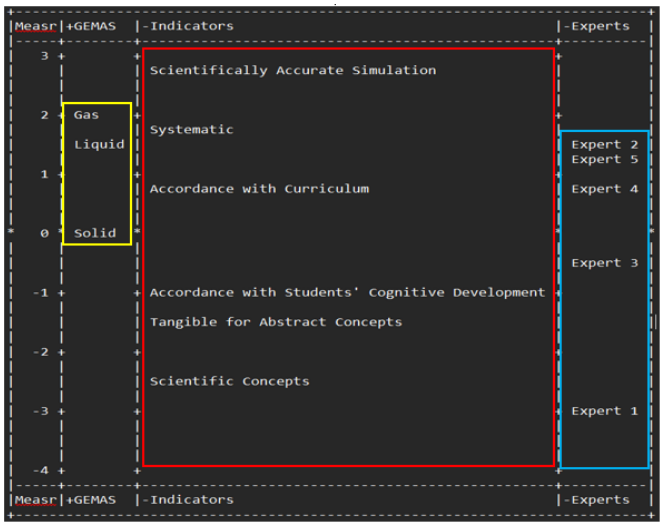

Figure 14. Content Validation of GEMAS-Vertical Rulers

Each of these aspects has been rigorously assessed to ensure that GEMAS supports accurate, engaging, and pedagogically sound learning experiences. The highest-ranking indicators, such as "scientifically accurate simulation" and "systematic design," scored well above zero logits, affirming GEMAS's effectiveness in presenting scientifically accurate content in a structured and reliable manner. The indicator "accordance with curriculum" also scored positively, demonstrating that GEMAS aligns with established educational standards.

This alignment confirms that the game is not only relevant to the learning objectives of its target audience but also capable of supporting meaningful educational outcomes.

The Wright Map further shows that "accordance with students' cognitive development" and "tangible for abstract concepts" indicators are moderately effective, indicating GEMAS's ability to make abstract scientific principles accessible to students. While there is room for improvement in enhancing its cognitive alignment, the game has already proven effective in engaging learners with varying levels of understanding. When analyzing the phase structure subsections, the gas phase demonstrated the highest validity with its exceptional visualization of molecular motion and particle spacing, followed by the liquid phase, which also received strong ratings for its accurate depictions of fluidity. However, the solid phase scored lower on the logit scale due to expert concerns regarding its scientific accuracy. These concerns, while notable, do not detract from the overall validity of GEMAS but instead highlight an opportunity for refinement in this specific content area (Sumintono, 2018).

Overall, the findings confirm that GEMAS content validity is sound. The strengths in scientific accuracy, systematic design, and curriculum alignment establish GEMAS as a reliable and effective educational game. The identified areas for improvement, particularly in the solid-phase representations, provide valuable feedback for further enhancement, ensuring that GEMAS continues to support scientifically accurate and engaging learning experiences for students.

The unidimensionality of GEMAS (see Figure 15) was assessed based on the "variance explained by Rasch measures," which accounted for 51.78% of the total variance in the data. This percentage reflects that the majority of the observed variation is attributed to the primary latent trait that GEMAS aims to measure.

		Count	Mean	S.D.
Responses non-extreme estimable	=	90	2,63	0,48
Count of measurable responses	=	90		
Raw-score variance of observations	=	0,232	100.00%	
Variance explained by Rasch measures	=	0,120	51,78%	
Variance of residuals	=	0,112	48,22%	

Figure 15. Unidimensionality of GEMAS-Content Validity

According to Rasch model standards, a variance explanation above 50% is a strong indicator of unidimensionality, meaning the instrument focuses on a single underlying construct or concept. This ensures that the results derived from the analysis accurately represent the targeted content validity of GEMAS, without being confounded by unrelated factors or noise (Engelhard Jr, 2013; Maryati et al., 2019).

The high percentage of variance explained demonstrates that GEMAS effectively captures the core dimension it was designed to evaluate, which in this case aligns with its goal of assessing scientifically accurate visualizations and systematic learning content. Such a level of unidimensionality is crucial for ensuring that the validity of GEMAS is not compromised by extraneous variables, such as inconsistent expert judgments or irrelevant criteria. The result signifies that GEMAS is robust in its structure and provides meaningful, reliable insights into the scientific accuracy and curriculum alignment of its content. This further strengthens the validity of GEMAS as an educational tool, ensuring its effectiveness for its intended purposes. Thus, the unidimensionality analysis provides evidence that GEMAS effectively measures the intended construct, contributing to its overall content validity.

The GEMAS (Game for Microscopic Atom Simulation) content validity was assessed using Many-Faceted Rasch Measurement (MFRM) analysis. The evaluation involved multiple facets, including the raters, criteria, and individual items (see Figure 16). The fit statistics, reliability, and inter-rater agreement were carefully examined to determine the quality and validity of the content.

Total Score	Total Count	Obsvd Average	Fair(M) Average	- Measure	Model S.E.	Infit MnSq	Infit ZStd	Outfit MnSq	Outfit ZStd	Estim. Discrm	Correlation PtMea	Correlation PtExp	Exact Agree. Obs %	Exact Agree. Exp %	N	Experts
45	18	2.50	2.49	1.19	.64	.47	-1.8	.32	-1.2	1.64	.84	.68	66.7	66.6	5	Expert 5
53	18	2.94	2.99	-3.10	1.11	1.06	.3	.32	1.1	1.05	.33	.33	61.1	59.2	1	Expert 1
44	18	2.44	2.39	1.59	.64	.74	-.7	.81	.0	1.25	.73	.67	59.7	64.3	2	Expert 2
49	18	2.72	2.84	-.48	.68	.92	-.1	1.41	.6	.95	.58	.62	66.7	69.2	3	Expert 3
46	18	2.56	2.59	.79	.64	1.72	1.8	1.58	.9	.19	.43	.68	62.5	68.3	4	Expert 4
47.4	18.0	2.63	2.66	.00	.74	.98	-.1	.89	.3		.58				Mean (Count: 5)	
3.3	.0	.18	.22	1.70	.19	.42	1.2	.53	.9		.19				S.D. (Population)	
3.6	.0	.20	.25	1.90	.21	.47	1.4	.59	1.0		.21				S.D. (Sample)	

Model, Populn: RMSE .76 Adj (True) S.D. 1.52 Separation 1.99 Strata 2.98 Reliability (not inter-rater) .80
Model, Sample: RMSE .76 Adj (True) S.D. 1.74 Separation 2.28 Strata 3.37 Reliability (not inter-rater) .84
Model, Fixed (all same) chi-squared: 16.9 d.f.: 4 significance (probability): .00
Model, Random (normal) chi-squared: 3.4 d.f.: 3 significance (probability): .33
Inter-Rater agreement opportunities: 180 Exact agreements: 114 = 63.3% Expected: 118.0 = 65.5%

Fair·average·across·experts¶ Outfit·MnSq¶ Reliability¶

Figure 16. Content Validity of GEMAS-Measurement Report

The fit statistics revealed that the average Infit Mean-Square (MNSQ) value across the model was approximately 1.01, which falls within the acceptable range of 0.5 to 1.5. This indicates that most of the criteria items behaved as expected within the framework of the Rasch model. However, there were a few items and rater behaviors that slightly exceeded the threshold, such as Expert 1, whose Infit MNSQ value approached the upper limit. Similarly, the Outfit MNSQ statistics demonstrated comparable trends, with some deviations, but overall, the values adhered closely to the desired model-fit criteria. These findings support the overall validity of the GEMAS content evaluation.

In terms of separation and reliability, the data provided further evidence of the robustness of the evaluation process. The separation indices for the population and sample strata were calculated to be 2.98 and 3.37, respectively. These values indicate a clear differentiation between levels of difficulty among the criteria items and the severity levels among raters. The strata indices suggested that there were approximately three to four distinct levels of difficulty among the criteria, ensuring that the measurement scale was effectively capturing variation. Reliability scores of 0.80 for the population and 0.84 for the sample demonstrated strong internal consistency, confirming that the assessment process was both reliable and replicable.

Inter-rater agreement was another critical aspect of the analysis. The observed exact agreement among the raters was 63.3%, which exceeded the minimum acceptable threshold of 50%. This level of agreement highlighted a moderate degree of consistency among the raters, although it also indicated room for improvement in achieving complete uniformity. The variability in rater severity was evident from their measures on the logit scale. For instance, Expert 5 emerged as the most lenient rater, assigning lower logit values, whereas Expert 4 showed the highest severity with elevated logit scores. Despite these variations, the overall distribution of rater severity was balanced, with no extreme outliers, supporting the validity of the aggregated evaluations (Eckes, 2019). The criteria and items used in the assessment demonstrated strong alignment with the content validity framework. The total score across items was close to the maximum possible score, suggesting that GEMAS met most of the expected content validity criteria. Nonetheless, a few items were flagged for misfit based on their MNSQ values, which indicated that they may require further review and refinement to improve their alignment with the Rasch model.

In conclusion, the MFRM analysis confirmed that GEMAS exhibits high reliability and adequate fit to the Rasch model, ensuring its validity as an educational tool. The separation indices and reliability scores underscore the robustness of the evaluation process, while the inter-rater agreement reflects a moderate level of consistency among the experts. Although a few misfit items need revision, the overall findings affirm that GEMAS is a valid and reliable instrument for assessing its intended constructs. High validity in fluid/gas phases (logits > +1.0) suggests GEMAS excels in visualizing dynamic systems, addressing post-pandemic demands for tools that transcend textbook limitations.

3.5. Construct Validity

Figure 17 presents a Wright Map derived from FACETS software, which is used to assess the construct validity of GEMAS (Game for Microscopic Atom Simulation). The first column depicts the measurement scale in logits, ranging from approximately -2 to +3. This scale allows us to evaluate the relative difficulty or quality associated with various indicators and rater severities. The second column, labeled as "Media," indicates GEMAS as the target media being validated.



Figure 17. Construct Validity of GEMAS-Measurement Report

The third column represents the distribution of indicators that assess various aspects of GEMAS. These indicators are categorized based on qualities such as "Captivating Illustration," "Clear and Guided Instructions," "Accordance with PUEBI," "Promotes Visual Learning," "Unity of Design," "Appropriate Animation Simulation," "Coherence between Paragraphs and Sentences," "Attractive," "Clear Sentences," "Easily Understood Language," and "Consistent Terms and Symbols." The indicators are distributed along the logit scale, reflecting their relative difficulty or frequency of positive evaluations. The fourth column represents the severity or leniency of the raters involved in evaluating GEMAS. These raters are labeled Expert 1 through Expert 5. The distribution of

rater severity spans from slightly lenient to more stringent evaluations. The proximity of rater severities near the zero-point logit suggests minimal bias, indicating a generally consistent assessment across raters.

The chart reflects a balance between indicators of difficulty and rater stringency. Indicators positioned higher on the logit scale, such as "Coherence between Paragraphs and Sentences" and "Unity of Design," may represent more challenging criteria for GEMAS to meet, as indicated by their placement. Conversely, indicators lower on the scale, such as "Clear Sentences" and "Easily Understood Language," suggest that GEMAS more readily meets these criteria. The FACETS analysis demonstrates that GEMAS successfully aligns with multiple construct validity criteria, given the distribution of indicators across a moderate range of logits. Raters provided consistent evaluations across the identified indicators, further corroborating GEMAS's validity. This is evidenced by the clustering of rater severity measures near the zero-point logit and the logical distribution of indicators.

Overall based on the Wright Map and FACETS analysis, the construct validity of GEMAS is deemed valid. The distribution of indicators across the logit scale, the alignment with rater evaluations, and the balance between difficulty levels all point toward a robust and reliable measurement of GEMAS's construct validity. This outcome substantiates the quality and effectiveness of GEMAS in meeting the defined educational criteria and usability standards. The reliability metrics position GEMAS as a robust tool for low-resource settings, where teacher expertise varies widely.

The pandemic amplified longstanding challenges in e-teaching, revealing critical flaws such as overreliance on passive video instruction, limited interactivity, and disparities in access to essential learning tools (UNICEF, 2022). Remote learning environments often lacked hands-on engagement, restricting students' ability to develop deeper conceptual understanding. Addressing these gaps, GEMAS integrates interactive simulations that enhance learning by providing visually immersive experiences, compensating for the absence of physical experimentation. Its adaptable digital framework offers a scalable solution for post-pandemic education, aligning with the need for accessible and effective e-learning tools in underserved regions (UNICEF, 2022).

4. Conclusion

The MFRM analysis affirmed GEMAS's validity, with expert evaluations surpassing expectations across all criteria—including curriculum alignment, scientific accuracy, and user engagement. These results position GEMAS as a rigorously validated tool ready to address persistent misconceptions in phase structures, particularly in post-pandemic contexts where traditional labs remain inaccessible. This study contributes three key advancements: (1) a 3D simulation tool (GEMAS) tailored to phase structure misconceptions, (2) a methodological framework integrating the 3D model with MFRM for robust educational validation, and (3) empirical evidence supporting game-based learning as a scalable pedagogical strategy in hybrid/post-pandemic classrooms. By bridging gaps in interactivity and accessibility, GEMAS offers educators and developers actionable insights to reimagine STEM education, ensuring equitable opportunities for conceptual mastery in an increasingly digital world.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

This research was supported by Riset Kolaborasi LPTK Indonesia (RKLI), Lembaga Penelitian dan Pengabdian kepada Masyarakat (LPPM) Universitas Pendidikan Indonesia, and Fakultas Pendidikan Matematika dan Ilmu Pengetahuan Alam (FPMIPA) Universitas Pendidikan Indonesia. We extend our sincere gratitude for their valuable support and funding, which have significantly contributed to the success of this study.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Adimayuda, R., Sari, L., Ismail, A., Amalia, I. F., Gumilar, S., & Samsudin, A. (2021). Assessing two-dimensional collisions second-years students using PhET simulations on momentum and impulse concept. *Journal of Physics: Conference Series*, *1869*(1). https://doi.org/10.1088/1742-6596/1869/1/012204

Agiande, D. U., Williams, J. J., Dunnamah, A. Y., & Tumba, D. P. (2015). Conceptual Change Theory As A Teaching Strategy In Environmental Education. *European Scientific Journal*, *11*(35), 1857–7881.

Amalia, S. H., Purwanto, A., & Risdianto, E. (2024). Pengembangan Media Pembelajaran Game Edukasi Fisika (GEMIKA) Berbantuan Wordwall Untuk Meningkatkan Motivasi Belajar Siswa SMA. *Jurnal Penelitian Pembelajaran Fisika*, *15*(2), 222–232. https://doi.org/10.26877/jp2f.v15i2.18099

Aminudin, A. H., Adimayuda, R., Kaniawati, I., Suhendi, E., Samsudin, A., & Coştu, B. (2019). Rasch analysis of Multitier Open-ended Light-Wave Instrument (MOLWI): Developing and assessing second-years sundanese-scholars alternative conceptions. *Journal for the Education of Gifted Young Scientists*, *7*(3), 557–579. https://doi.org/10.17478/jegys.574524

Belova, N., & Zowada, C. (2020). Innovating higher education via game-based learning on misconceptions. *Education Sciences*, *10*(9), 1–10. https://doi.org/10.3390/educsci10090221

Bruner, J. (1966). *LEARNING ABOUT LEARNING, A CONFERENCE REPORT.*

Candrawati, E., Eko Sardjono, R., Rohman, I., & Kurnia Prahani, B. (2024). Implementation of Computational Thinking through Game-Based Learning: A Systematic Literature Review. *KnE Social Sciences*. https://doi.org/10.18502/kss.v9i8.15653

Cardinot, A., & Fairfield, J. A. (2019). Game-based learning to engage students with physics and astronomy using a board game. *International Journal of Game-Based Learning*, *9*(1), 42–57. https://doi.org/10.4018/IJGBL.2019010104

Chaudhry, F., Inam, M., Choudhry, H., Bashir, A., Ul Haq, K., & Riaz, H. (2021). Comparative Study on the Digital Game and Computer Simulation to Curtail Student's Misconception about Heat and Temperature. *European J of Physics Education*, *12*(2), 1309.

Eckes, T. (2019). Many-facet Rasch measurement. *Quantitative Data Analysis for Language Assessment Volume I*. https://api.semanticscholar.org/CorpusID:245350

Engelhard Jr, G. (2013). *Invariant measurement: Using Rasch models in the social, behavioral, and health sciences*. Routledge.

Febrianti, J., Akhsan, H., & Muslim, M. (2019). ANALISIS MISKONSEPSI SUHU DAN KALOR PADA SISWA SMA NEGERI 3 TANJUNG RAJA. *Journal of Innovation and Physics Learning*, *06*(1), 90–102.

Foster, A. N., Koehler, M. J., & Mishra, P. (2006). *Game-based learning of physics content: the effectiveness of a physics game for learning basic physics concepts*. https://www.researchgate.net/publication/257069307

Fratiwi, N. J., Samsudin, A., Ramalis, T. R., & Costu, B. (2020). Changing students' conceptions of Newton's second law through express-refute-investigate-clarify (ERIC) text. *Universal Journal of Educational Research*, *8*(6), 2701–2709. https://doi.org/10.13189/ujer.2020.080655

Haryadi, R., & Pujiastuti, H. (2020). *The Effectiveness of Using Serious Games to Improve Physics Learning Outcomes in Light Concept*. https://doi.org/10.21009/1

Haryono, H. E., Aini, K. N., Samsudin, A., & Siahaan, P. (2021). Reducing the students' misconceptions on the theory of heat through cognitive conflict instruction (CCI). *AIP Conference Proceedings*, *2330*. https://doi.org/10.1063/5.0043400

Irwansyah, I., Sukarmin, S., & Harjana, H. (2018). Development of Three-Tier Diagnostics Instruments on Students Misconception Test in Fluid Concept. *Jurnal Ilmiah Pendidikan Fisika Al-Biruni*, *7*(2), 207–217. https://doi.org/10.24042/jipfalbiruni.v7i2.2703

Kaniawati, I., Danawan, A., Suyana, I., Samsudin, A., & Suhendi, E. (2021). Implementation of Interactive Conceptual Instruction (ICI) With Computer Simulation: Impact of Students' Misconceptions on Momentum and Impulse Material. *Jurnal Ilmiah Pendidikan Fisika Al-Biruni*, *10*(1), 1–17. https://doi.org/10.24042/jipfalbiruni.v10i1.8375

Laurenty, F., Sulsilah, H., Amin, A. M., Samsudin, A., & Rusdiana, D. (2021). Enhancing conceptual understanding via Diffraction Grating Innovative Media (DIAGRAM). *Journal of Physics: Conference Series*, *2098*(1). https://doi.org/10.1088/1742-6596/2098/1/012013

Li, Y., Chen, D., & Deng, X. (2024). The impact of digital educational games on student's motivation for learning: The mediating effect of learning engagement and the moderating effect of the digital environment. *PLoS ONE*, *19*(1 January). https://doi.org/10.1371/journal.pone.0294350

Ma'ruf, M., Setiawan, A., Suhandi, A., & Siahaan, P. (2021). Trends in the Development of Physics Learning Multimedia in Indonesia: A Literature Review. *Jurnal Pendidikan Fisika*, *9*(3), 185–192. https://doi.org/10.26618/jpf.v9i3.5853

Maryati, M., Prasetyo, Z. K., Wilujeng, I., & Sumintono, B. (2019). Measuring Teachers'pedagogical Content Knowledge Using Many-Facet Rasch Model. *Jurnal Cakrawala Pendidikan*, *38*(3), 452–464.

Nurhasanah, N., Samsudin, A., Linuwih, S., & Sutrisno, A. D. (2022). Is SiPOERT an Innovative Learning? Implementation and Identification of Students' Conception on Simple Harmonic Motion. *Indonesian Journal on Learning and Advanced Education (IJOLAE)*, *5*(1), 78–91. https://doi.org/10.23917/ijolae.v5i1.19567

Nurul, S., Silung, W., Kusairi, S., & Zulaikah, S. (2016). Diagnosis Miskonsepsi Siswa SMA di Kota Malang pada Konsep Suhu dan Kalor Menggunakan Three Tier Test. *Jurnal Pendidikan Fisika Dan Teknologi*, *II*(3), 95–105.

Pratama, I. A., Subiki, S., & Harijanto, A. (2023). Pengembangan Media Pembelajaran Interaktif Fisika Sma Berbasis Adobe Animate Cc Pada Materi Hukum Gravitasi Newton. *Jurnal Pendidikan Fisika*, *11*(1), 17. https://doi.org/10.24127/jpf.v11i1.5818

Rino, A. P. A., Ruhiyat, Y., & Wibowo, F. C. (2019). Pengembangan Media Physics Game Learning pada Konsep Perubahan Wujud Zat. *Unnes Physics Education Journal*, *8*(1), 61–65. http://journal.unnes.ac.id/sju/index.php/upej

Samsudin, A. (2023). Conceptual Change based on Virtual Media (CC-VM) versus POE Strategy: Analysis of Mental Model Improvement and Changes on Light Wave Concepts. *International Journal of Technology in Education and Science*, *7*(2), 230–252. https://doi.org/10.46328/ijtes.449

Samsudin, A., Suhandi, A., Linuwih, S., Kaniawati, I., Fauzi, D. M., Aminudin, A. H., Fratiwi, N. J., & Adimayuda, R. (2023). Preliminary development of simulation on refutational-text (sort) to change conception of physics: Rasch and nvivo analysis. *AIP Conference Proceedings*, *2614*(1).

Soeharto, Csapó, B., Sarimanah, E., Dewi, F. I., & Sabri, T. (2019). A review of students' common misconceptions in science and their diagnostic assessment tools. *Jurnal Pendidikan IPA Indonesia*, *8*(2), 247–266. https://doi.org/10.15294/jpii.v8i2.18649

Suhandi, A., Samsudin, A., Suhendi, E., & Basori, H. (2020). Using CCOText assisted by dynamic model and analogy to fostering students' misconception about the concept of heat conduction. *Journal of Physics: Conference Series*, *1521*(2). https://doi.org/10.1088/1742-6596/1521/2/022044

Sumintono, B. (2018). Rasch model measurements as tools in assesment for learning. *1st International Conference on Education Innovation (ICEI 2017)*, 38–42.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285.

Tumanggor, A. M. R., Supahar, S., Ringo, E. S., & Harliadi, M. D. (2020). Detecting Students' Misconception in Simple Harmonic Motion Concepts Using Four-Tier Diagnostic Test Instruments. *Jurnal Ilmiah Pendidikan Fisika Al-Biruni*, *9*(1), 21–31. https://doi.org/10.24042/jipfalbiruni.v9i1.4571

Umar, F. A., Samsudin, A., Ramalis, T. R., Sa'diyah, L. H., Dalila, A. A., & Komalasari, K. (2021). Uyo and nanu misconception investigation (UNAMI) on sound-light waves materials in North Sulawesi. *Journal of Physics: Conference Series*, *2098*(1). https://doi.org/10.1088/1742-6596/2098/1/012027

UNICEF. (2022). *The Impact of the COVID-19 Pandemic on Children's Learning in Indonesia*.

Widiasih, W., Zakirman, Z., & Ekawati, R. (2023). Development of Augmented Reality Media to Improve Student Understanding of Optical Eyes System Materials. *Jurnal Penelitian Pendidikan IPA*, *9*(2), 912–919. https://doi.org/10.29303/jppipa.v9i2.2858

Wulandari, T. A., & Prihandono, T. (2018). Analisis Miskonsepsi Siswa Pada Materi Suhu Dan Kalor Di Kelas Xi Sma Jember. *Seminar Nasional Pendidikan Fisika*, *3*, 135–139.

Yun, R., Wang, M., & Li, Y. (2008). Design and Implementation of Game-Based Learning Environment for Scientific Inquiry. In *LNCS* (Vol. 5093).