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DESIGN AND VALIDATION OF A MULTI-INTERACTION-BASED AUGMENTED REALITY LEARNING MODEL TO OVERCOME ABSTRACTNESS IN PHYSICS CONCEPTS AT THE SECONDARY EDUCATION LEVEL

DESENHO E VALIDAÇÃO DE UM MODELO DE APRENDIZAGEM DE REALIDADE AUMENTADA BASEADO EM MULTI-INTERAÇÕES PARA SUPERAR A ABSTRAÇÃO EM CONCEITOS DE FÍSICA NO NÍVEL DE ENSINO MÉDIO

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Abstract
This study aims to test the effectiveness of Augmented Reality (AR)-based learning models with a multi-interaction approach in improving the quality of physics learning, especially in wave and force materials. Using a quasi-experimental design with a pretest-posttest control group, the study involved high school students who were divided into experimental and control groups. Data was collected through concept comprehension tests, motivational questionnaires, inquiry engagement observation sheets, and student and teacher responses. The results of the study showed that the AR-based model significantly improved students' understanding of concepts, as seen from the increase in posttest scores. In addition, students in the experimental group showed higher learning motivation, involvement in scientific inquiry, and positive perception of learning than the control group. This model facilitates the interactive visualization of abstract concepts and supports a variety of learning styles through simulations and collaborative activities. Teachers also responded positively, assessing this model as technologically relevant and effective for learning differentiation. Although additional technical training is needed, this model is considered feasible to be applied in the context of 21st-century learning. The results of this study support the integration of AR as an

Resumo
Este estudo tem como objetivo testar a eficácia de modelos de aprendizagem baseados em Realidade Aumentada (RA) com uma abordagem multiinteração na melhoria da qualidade da aprendizagem de física, especialmente em materiais de onda e força. Utilizando um delineamento quase experimental com um grupo controle pré-teste-pós-teste, o estudo envolveu alunos do ensino médio, divididos em grupos experimental e controle. Os dados foram coletados por meio de testes de compreensão de conceitos, questionários motivacionais, folhas de observação de engajamento em investigação e respostas de alunos e professores. Os resultados do estudo mostraram que o modelo baseado em RA melhorou significativamente a compreensão dos conceitos pelos alunos, como observado pelo aumento nas pontuações pós-teste. Além disso, os alunos do grupo experimental demonstraram maior motivação para a aprendizagem, envolvimento em investigação científica e percepção positiva da aprendizagem do que o grupo controle. Este modelo facilita a visualização interativa de conceitos abstratos e oferece suporte a uma variedade de estilos de aprendizagem por meio de simulações e atividades colaborativas. Os professores também responderam positivamente, avaliando este modelo como tecnologicamente relevante e eficaz para a diferenciação da aprendizagem.

innovative strategy in physics learning that is more contextual, participatory, and student-centered.

Keywords: Augmented Reality. Conceptual Understanding. Multi-Interaction Learning Model. Physics Education. Secondary Education.

Embora seja necessário treinamento técnico adicional, este modelo é considerado viável para ser aplicado no contexto da aprendizagem do século XXI. Os resultados deste estudo corroboram a integração da RA como uma estratégia inovadora na aprendizagem de física, mais contextual, participativa e centrada no aluno.

Palavras-chave: *Realidade Aumentada. Compreensão Conceitual. Modelo de Aprendizagem Multiinteracional. Educação em Física. Ensino Médio.*

1 INTRODUCTION

Physics learning at the secondary school level often faces obstacles due to the high level of abstraction of concepts such as force, motion, and electric fields, which are difficult to visualize and rarely experienced directly by students. This often leads to misconceptions, low understanding, and a lack of motivation to learn (Tindan & Arthur, 2024; Mualem & Eylon, 2007; Rohmah, 2017; Cao & Yu, 2023). Conventional methods such as lectures and 2D media have proven to be less effective in building students' mental representations of these concepts (Gao *et al*., 2024; Ozdemir *et al*., 2018).

In response to educational challenges, digital technology encourages the use of Augmented Reality (AR) as an innovative learning medium. AR combines virtual objects into the real world interactively, helping to visualize abstract concepts in concrete terms (Al-Ansi *et al*., 2023; Waxman & Goldie, 2009; Rahmat *et al*., 2024; Joshua Chukwuemeka *et al*., 2020; Agbo *et al*., 2023). Studies show that AR effectively improves students' understanding of concepts, motivation, and engagement, as well as encourages exploration and scientific thinking skills (Yoon *et al*., 2017; Ansori *et al*., 2025; Fitri *et al*., 2025; Cai *et al*., 2023; Cao & Yu, 2023; B. Yoon, 2021; Kairu, 2021).

Although AR research in physics education is increasing, it still largely highlights aspects of technology and general learning outcomes, rather than pedagogical designs based on structured interactions (Reyaz Ahmad Bhat, 2023; Bizami *et al*., 2023; Agbo *et al*., 2023; Al-Masarweh, 2021; Sung *et al*., 2016). Few studies have examined AR-based physics learning models with systematic multi-interaction integration. In fact, visual, manipulative, reflective, and collaborative interactions are essential to build students' conceptual understanding and critical thinking skills. (Astuti *et al*., 2024; Altinpulluk, 2019; Warkentin *et al*., 2025; Opiyo & Horváth, 2010; Vidak *et al*., 2024; Alzahrani, 2020; Agbo *et al*., 2023; Wen *et al*., 2023).

Research on the effectiveness of AR models in reducing the abstraction of physics concepts is still limited. Most studies only use AR as a visual tool without a clear pedagogical approach, even though meaningful interactivity is essential in inquiry learning. (Cai *et al*., 2023; Warkentin *et al*., 2025; Radu *et al*., 2023; Vidak *et al*., 2024). In addition, empirical validation of multi-interaction AR model design in terms of effectiveness, efficiency, and user acceptability is still rarely done.

This research aims to fill the literature gap by developing and validating an Augmented Reality-based physics learning model that integrates the principle of multi-interaction to overcome abstract physics concepts at the intermediate level. The model is designed to deliver interactive visual experiences, encourage reflection, and collaborative discussion in inquiry-based learning. (Bouchey *et al*., 2021; Bizami *et al*., 2023; Amna Saleem *et al*., 2021; Wen *et al*., 2023). Its effectiveness was tested through a quasi-experimental approach and qualitative analysis of students' concept understanding, learning motivation, and inquiry style.

Thus, this research not only contributes to the development of technology-based pedagogical innovations, but also offers novelty in the form of: (1) the development of multi-interaction-based and pedagogically oriented AR learning models; (2) comprehensive empirical validation of the effectiveness of the model in overcoming abstraction of physical concepts; and (3) the preparation of AR design principles and implementation in the context of physics learning that can be replicated by educators at various levels. This research is expected to be a scientific and practical basis for the application of immersive technology in science learning, as well as to enrich the limited technology-based physics education literature.

As a lecturer in Basic Physics at Wira Bhakti University, the researcher has expertise in technology-based physics learning design. The experience of teaching and researching reinforces the belief that students' main difficulty is forming conceptual representations of abstract phenomena.

Researchers consistently apply dynamic visualization, high interactivity, and constructivist approaches in teaching media. Involvement in device development and teacher training shows that proper learning design can drive the transformation of science learning in schools.

This research is a manifestation of the researcher's commitment to developing innovative and applicable learning models and is expected to make a real contribution to physics education and strengthen the role of universities in advancing technology-based learning strategies in Indonesia.

2 LITERATURE REVIEW & THEORETICAL FRAMEWORK

2.1 Physics learning and concept abstraction

Physics involves abstract and complex concepts that are difficult for students to grasp without concrete representations. (Ansori *et al*., 2025; (Jesionkowska *et al*., 2020; Abdullah *et al*., 2022; Garzón *et al*., 2019). Misconceptions often arise from the lack of effective mental models, caused by limited media and non-interactive approaches (Duit & Treagust, 2003; Duit *et al*., 2013). Tindan & Arthur (2024) also found that students struggle to understand cause-and-effect in physical phenomena due to the absence of contextual and interactive learning. (Al-Masarweh, 2021; Radu *et al*., 2023).

Physics, as a discipline, is characterized by abstract and complex concepts. (Fitri *et al*., 2025; Mualem & Eylon, 2007). Concepts such as force, acceleration, electric and magnetic fields, or electromagnetic waves are difficult for students to grasp without concrete representations. (Tindan & Arthur, 2024; Al-Masarweh, 2021; Koumpouros, 2024; Jesionkowska *et al*., 2020). According to Duit *et al*. (2013), misconceptions in science learning, particularly in physics, are largely caused by the failure to develop appropriate mental representations due to limitations in media and instructional approaches. This is supported by the findings of Tindan & Arthur (2024), which show that many students struggle to understand cause-and-effect relationships in physical phenomena due to instructional approaches that lack interactivity and contextual relevance.

More recent research by Pierson *et al*. (2021) in the International Journal of Science Education emphasizes the importance of multimodal approaches and technology-based visualizations in addressing the abstract nature of concepts in science learning (Dewantara, 2015; Syskowski *et al*., 2024). They found that the use of interactive, digital-based technologies can help students construct meaning through visual and spatial experiences.

2.2 Augmented reality dalam pembelajaran fisika

Augmented Reality (AR) technology is one of the fastest-growing innovations in the field of education, especially in science learning. AR enables real-time integration of real-world and virtual objects in a 3D visual format that users can manipulate, explore, and observe (Brannon Barhorst *et al*., 2021). This ability makes AR a potential medium to bridge the gap between abstract concepts and concrete experiences in physics learning. (Astuti *et al*., 2024; Fidan & Tuncel, 2019; Al-Masarweh, 2021; Jesionkowska *et al*., 2020).

Empirical research supports the effectiveness of AR in improving the quality of learning. Delgado-Kloos (2018), through experiments on physics learning, found that the use of AR significantly improved students' cognitive engagement, concept comprehension, and information retention. The visual representations provided by AR have been shown to help students form a deeper understanding of physical phenomena that are difficult to observe directly, such as electric fields and parabolic motion. (Huang *et al*., 2016; (Gao *et al*., 2024).

A study by Al-Masarweh (2021) also showed that the implementation of smartglasses-based AR in learning Lorentz magnetic field concepts significantly improved students' understanding, with 83% of students reporting an increase in comprehension and usability scores of 81/100. This indicates that visual and interactive learning experiences can effectively reinforce students' conceptual mental representations.

In addition, a systematic review by Vidak *et al*. (2024) confirms that AR has the advantage of facilitating learning through complementary visualization, cognitive load optimization, task time efficiency, and increased collaboration and scientific inquiry. (Saidin *et al*., 2015; Bacca *et al*., 2014; Ozdemir *et al*., 2018; Cleaver *et al*., 2021). These elements are in line with modern pedagogical principles that emphasize active, student-centered learning. (Bizami *et al*., 2023).

To maximize the potential of AR in education, the XR-Ed framework emphasizes the importance of paying attention to aspects of physical accessibility, social interactivity, degrees of virtuality, and adaptivity (Yang *et al*., 2020). Effective AR app design also needs to consider parameters such as interactivity, immersion, proximity to reality, complexity, and game elements (Abdallah *et al*., 2024; Syskowski *et al*., 2024; Kairu, 2021). The integration of these aspects can increase the effectiveness of AR in supporting an immersive, contextual, and collaborative learning process.

Thus, AR is not only a visual aid but also an innovative learning model that supports a multi-interaction approach, encompassing visualization, manipulation, reflection, and collaboration relevant to the demands of 21st-century learning. (Bouchey *et al*., 2021; Mayer, 2012).

2.3 Multi-interaction-based learning model

AR becomes more effective in education when integrated into a structured, multimodal learning model. This model combines visual (3D visualization), manipulative (object control), reflective (linking theory and phenomena), and collaborative (group discussion or experiments) interactions. (Opiyo & Horváth, 2010).

According to Mayer in Waxman & Goldie (2009), on the Cognitive Theory of Multimedia Learning, effective learning occurs when students can build connections between verbal and visual representations. This is reinforced in technology-based learning that combines text, graphics, animation, and user interaction. (Astuti *et al*., 2024; Vidak *et al*., 2024; Wen *et al*., 2023; Radu *et al*., 2023). Learning designs like this can minimize cognitive load and increase knowledge transfer.

In physics learning, AR models integrated with active learning—through manipulation, exploration, and reflection can significantly enhance conceptual understanding (Cleaver *et al*., 2021; Computer Assisted Learning - 2024 - Gonnermann-Müller - Unlocking Augmented Reality Learning Design Based on Evidence From.Pdf, n.d.). They emphasize the importance of integrating technology design and pedagogical strategies to create meaningful learning experiences.

2.4 Theoretical basis of research: cognitive theory and social constructivism

This research is based on two main theories.

This theory states that learning is more effective when verbal and visual information are integrated, and students control their interaction with the media. AR supports this by activating key cognitive processes like selecting, organizing, and integrating information with prior knowledge. (Waxman & Goldie, 2009; Mayer & Johnson, 2008; Moreno & Mayer, 2007).

Sociocultural Constructivism (Vygotsky, 1978)

This theory highlights that learning occurs through social interaction and tools like technology. (Amna Saleem *et al*., 2021; Altinpulluk, 2019; Huang & Liaw, 2018; Cheng & Tsai, 2013). In AR-based multi-interaction learning, students collaborate, discuss, and solve problems, with AR serving as a tool to support knowledge construction through shared and exploratory experiences. (Amna Saleem *et al*., 2021; Yildirim, 2008; Ryans, 1955).

Literature Gap and Relationship to Related Research

Although many international studies highlight AR's potential in education, few have examined AR-based physics models that explicitly integrate multi-interaction strategies. Most focus only on AR as a visual aid without a clear pedagogical framework. (Delgado-Kloos, 2018; Yoon *et al*., 2017). Few have examined how a variety of interactions (visual, manipulative, reflective, collaborative) can be designed synergistically in a structured learning model to address the abstraction of physical concepts.

Few studies have empirically validated the effectiveness of AR models in secondary physics education in Indonesia. This research addresses that gap by developing a multi-interaction AR model and testing its impact on students' conceptual understanding, motivation, and engagement.

3 METHODOLOGY

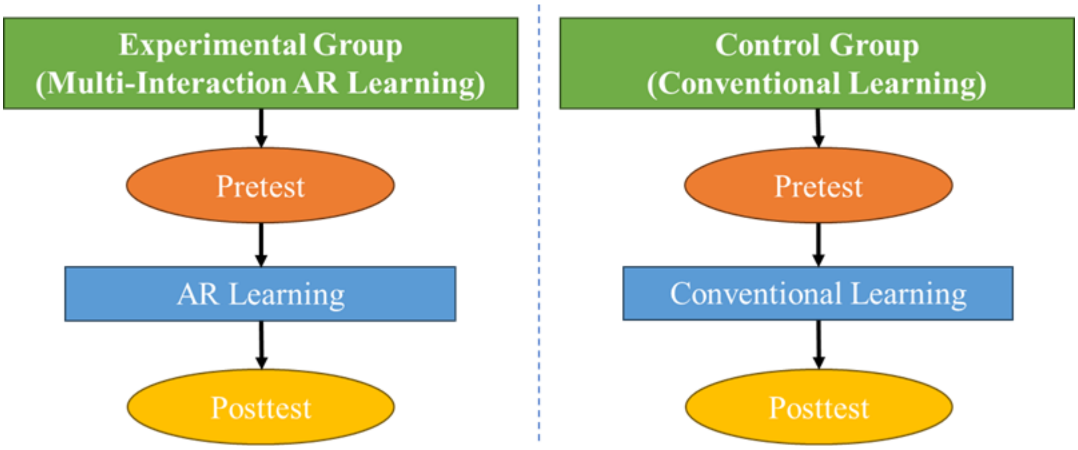
3.1 Research design

This study employs a Research and Development (R&D) approach to develop and evaluate an AR-based physics learning model with a multi-interaction approach. The model aims to enhance students' conceptual understanding, motivation, and inquiry skills, using the ADDIE framework (Analysis, Design, Development, Implementation, Evaluation). (Robert Maribe Branch, 2009; Joshua Chukwuemeka *et al*., 2020; Yang *et al*., 2020).

To test the model's effectiveness, a quasi-experimental pretest-posttest control group design was used, with one group using the multi-interaction AR model and the other using conventional methods (see Figure 1).

Figure 1.

Pretest-posttest control group design chart



3.2 Context and participants

This study involved 60 grade XI science students from three purposively selected high schools in South Sulawesi: SMA Negeri 1 Rantepao, SMA Negeri 1 Makale, and SMA Negeri 7 Makassar, based on digital infrastructure readiness, availability of physics teachers, and school support for technology-based learning. Students were divided into an experimental group using a multi-interaction AR model and a control group using conventional methods, with pretest scores used to ensure initial equivalence.

Two physics teachers from partner schools implemented the learning model, while five expert validators, two in learning design, two in educational technology, and one senior physics teacher ensured its validity by reviewing the model, AR media, and evaluation instruments.

3.3 Product development

This study produced an AR-based physics learning model with a multi-interaction approach to improve understanding of waves and forces. The model includes 3D visual modules, interactive activities (visual, manipulative, reflective, collaborative), and teacher-student guides. It features an Android AR app developed using Unity 3D and Vuforia SDK for virtual object exploration. Experts and teachers validated the design to ensure quality and relevance (see Figure 2).

Figure 2.

Stages of model development

3.4 Data collection instruments and techniques

Data were collected using four instruments: pretest–posttest to assess concept comprehension, Likert-scale questionnaires for motivation, observation sheets for inquiry engagement, and interviews for student and teacher responses. The test was aligned with national curriculum indicators and validated through pilot trials.

The validity test consisted of content and empirical validation. Content validity, assessed by three experts, yielded an Aiken's V of 0.87 (high). Empirical results showed 24 of 25 questions met the criteria; one item was revised. The instrument showed high reliability with a Cronbach's Alpha of α = 0.832, indicating strong internal consistency for measuring physics concept understanding.

4 DATA ANALYSIS TECHNIQUES

4.1 Quantitative analysis

4.1.1 Uzi Gain Score (N-Gain)

The first step was to calculate the normalized gain value (N-gain) to see the level of improvement in understanding physics concepts in each student, both in the experimental group (which used the multi-interaction AR model) and the control group (which used conventional learning methods).

The N-gain formula used is (Sesmiyanti *et al*., 2019):

$$\mathrm{N-gain} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}} \qquad (1)$$

The interpretation of the N-gain value in this study refers to three categories, namely: (1) < 0.3 is categorized as a low increase; (2) 0.3 - 0.7 is categorized as a moderate increase; and (3) > 0.7 is categorized as a high increase. This N-gain value is used to assess the effectiveness of improving learning outcomes, both individually and in groups, after the implementation of the learning model.

4.1.2 Normality and homogeneity test

Before the t-test is performed, the data is analyzed through a prerequisite test to ensure statistical feasibility. A normality test (Kolmogorov-Smirnov/Shapiro-Wilk, $\alpha = 0.05$) is used to check the distribution of the data, and the data is considered normal if $p > 0.05$. The homogeneity test (Levene's Test) was used to check the similarity of variance between groups, with the criterion $p > 0.05$. These two tests ensure that the t-test can be used validly.

4.1.3 Uji t (Independent Sample t-Test)

To test for significant differences between the learning outcomes of the experimental and control group students, a t-test of two independent samples was used.

This test compares the average posttest scores to assess the effectiveness of multi-interaction-based AR learning models compared to conventional methods. The test was performed at a significance level of 0.05; If the P-value < 0.05, then the difference is considered statistically significant. In addition, the effect size was calculated using Cohen's formula d to determine the strength of the influence of the applied learning model.

4.1.4 Descriptive statistical analysis for inquiry motivation and engagement

In addition to learning outcomes, this study also analyzes affective aspects and learning processes, namely: students' learning motivation and involvement in inquiry activities during physics learning. The analysis was carried out using descriptive statistics to determine the mean value, standard deviation, and percentage of response. Data were obtained through a learning motivation questionnaire and an inquiry engagement observation sheet.

The results of this analysis provide an overview of the extent to which the learning model increases student interest, curiosity, and active participation, and the suitability of the multi-interaction approach with the learning characteristics of 21st-century students.

4.2 Qualitative analysis

The qualitative data analysis approach in this study is used to explore the deep perceptions, experiences, and responses of students and teachers to the developed learning model. Emphasis is placed on the learning process, user reactions to AR media, as well as recommendations for improvement based on hands-on experience in the field.

4.2.1 Thematic analysis

Thematic analysis was used to interpret teacher and student interview data after the application of the learning model. The procedure begins with verbatim transcription, followed by initial coding to identify repeating patterns, and inductive development of themes based on meanings emerging from the data. To ensure reliability, the two researchers coded separately and compared the results, so that the themes obtained accurately reflected the participants' perceptions.

4.2.2 Data triangulation

To ensure the validity and reliability of the findings, data triangulation was carried out by integrating four sources: learning outcome tests, motivation questionnaires, engagement observations, and teacher-student interviews. The test measures understanding of concepts before and after learning, questionnaires assess motivation and interest in learning, observations record student activities while using AR, and interviews explore perceptions and experiences during the learning process.

Triangulation is used to ensure consistency between quantitative and qualitative data, as well as to uncover aspects that are not visible in the numbers, such as student enthusiasm. This approach strengthens the conclusion by incorporating various points of view. Quantitative data were analyzed using SPSS, while qualitative data were processed with NVivo to identify themes and patterns from interviews and observations.

5 ANALYSIS AND DISCUSSION

5.1 Data analysis

This study aims to develop and test the effectiveness of an Augmented Reality (AR)-based physics learning model with a multi-interaction approach to concept understanding, learning motivation, and student inquiry engagement. The results are presented according to the order of the data collection and analysis procedures, both quantitative and qualitative.

5.2 Improved understanding of physics concepts

Concept understanding is measured through a pretest and posttest with 25 multiple-choice questions. The results of the N-Gain analysis showed a significant increase in the experimental group. Data on improving understanding of Physics concepts (matter of waves and forces) of the experimental group and the control group are presented in Table 1.

Table 1.

Data on improving students' understanding of physics concepts

Group	Pretest Average	Posttest Average	N-Gain	Category
Experiment (n=30)	48,33	82,50	0,66	Keep
Control (n=30)	47,67	69,00	0,41	Keep

The results of the study showed that there was an increase in understanding of physics concepts in both groups after learning. The experimental group that used the multi-interaction-based Augmented Reality (AR) learning model experienced an average increase from a pretest score of 48.33 to 82.50 in the posttest. The N-Gain value obtained is 0.66, which belongs to the medium category, but is close to the high category.

Meanwhile, the control group that participated in conventional learning also increased, with an average pretest score of 47.67 and a posttest score of 69.00. The N-Gain value obtained was 0.41, which was also in the medium category, but relatively lower than that of the experimental group.

This comparison shows that multi-interaction-based AR models are more effective in improving understanding of physics concepts than conventional learning methods. Significant improvements in the experimental group reinforce the finding that the integration of interactive visual technology in learning can strengthen students' cognitive processes and reduce misconceptions about abstract material, such as waves and forces.

5.3 Statistical description of posttest results

The descriptive results of the posttest scores of the experimental class and the control class are shown in Table 2.

Table 2.

Data on the posttest scores of both classes

Group	N	Mean	Standard Deviation	Standard Error Mean
Experiment	30	82.50	6.94	1.27
Control	30	69.00	7.42	1.35

The results of the descriptive analysis of the posttest scores showed that the experimental group, who participated in learning using a multi-interaction-based Augmented Reality (AR) model, obtained an average score of 82.50 with a standard deviation of 6.94 and a standard error of 1.27. Meanwhile, the control group, who learned using conventional methods (lectures and print media), obtained an average score of 69.00, with a standard deviation of 7.42 and a standard error of 1.35.

The average difference of 13.50 points between the two groups indicated a significant improvement in learning outcomes in the experimental group. The relatively small standard deviation in both groups also showed that the spread of students' grades was in a fairly consistent range. In addition, a low standard error value reinforces the level of confidence in each group's average estimate.

In general, this data provides an early indication that the use of multi-interaction-based AR learning models has greater potential in improving understanding of physics concepts compared to conventional learning methods. Further analysis with inferential statistical tests is needed to test the significance of these differences more formally.

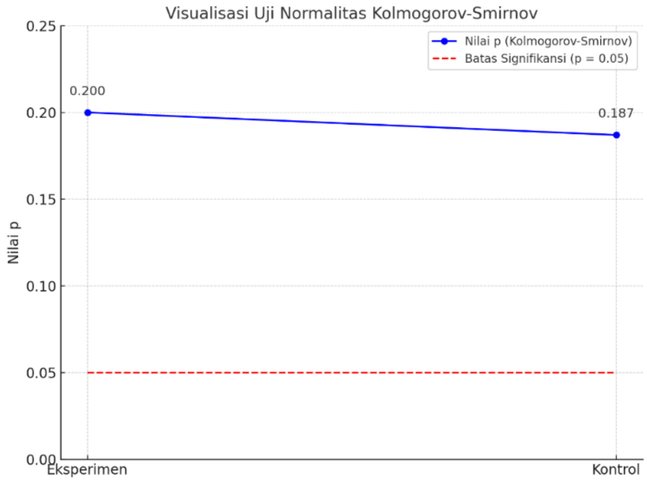
5.4 Assumption test: normality and homogeneity

5.4.1 Normality test (Kolmogorov-Smirnov)

The results of the normality test of the two classes (experimental class and control class) using the Kolmogorov-Smirnov method are presented in Figure 3.

Figure 3.

Data from the normality test results



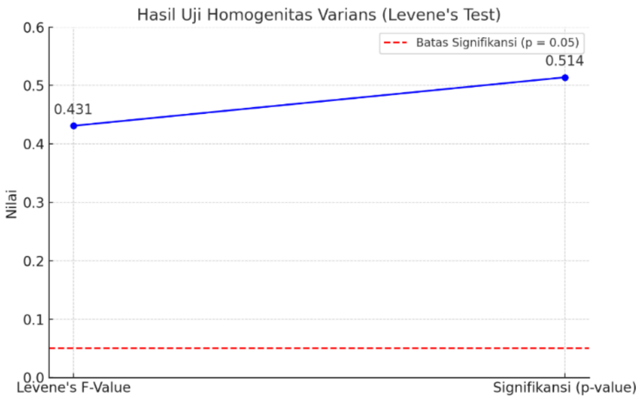
The Kolmogorov-Smirnov test showed p-values of 0.200 (experimental) and 0.187 (control), both > 0.05, indicating that the posttest data are normally distributed and suitable for parametric analysis, including the independent t-test.

5.4.2 Test of homogeneity of variance (Levene's Test)

The data from the homogeneity test of variance for the two groups using Levene's Test method are presented in a line diagram (Figure 4).

Figure 4.

Data from the homogeneity test results



The Levene's Test showed F = 0.431 and p = 0.514 (p > 0.05), indicating no significant variance difference between groups. This confirms homogeneity and supports the validity of using parametric tests like the t-test to assess the model's effectiveness.

5.5 Independent t-Test results

The effectiveness of the multi-interaction-based AR learning model on the understanding of physics concepts was analyzed through an independent sample t-test on the posttest score between the experimental and control groups. The t-test results of the SPSS output are shown in Table 3.

Table 3.

Results of the t-test

Levene's Test for Equality of Variances	t	df	Sig. (2-tailed)	Mean Difference	Std. Error	95% CI of Difference
Equal variances assumed	4.791	58	**0.000**	13.500	2.817	[7.860, 19.140]

The result t(58) = 4.791, p = 0.000 (p < 0.05) confirms a significant difference in posttest scores between the experimental and control groups. This indicates that the AR-based multi-interaction learning model is statistically effective in enhancing students' conceptual understanding of physics compared to conventional methods.

5.6 Learning motivation (descriptive analysis and score comparison)

Student motivation was measured using a Likert-scale questionnaire covering interest, engagement, relevance, confidence, and achievement drive. The analysis of responses to 20 statements is shown in Table 4.

Table 4.

Student learning motivation data

Measured Learning Motivation Indicators	Class			
	Experiment		Control	
	Average Score	Category	Average Score	Category
Interest in the material	4,53	Strongly agree	3,63	Agree
Active involvement in learning	4,2	Agree	3,17	Disagree
Perception of the relevance of the material	4,27	Agree	3,27	Disagree
Confidence in understanding the material	3,87	Agree	2,93	Disagree
Motivation to perform	3,97	Agree	2,87	Disagree
Average	**4,17**	**Agree**	**3,17**	**Disagree**

Based on the data, students' learning motivation in experimental classes using multi-interaction-based Augmented Reality (AR) models was consistently higher on all indicators than in control classes that learned conventionally.

On the interest indicator, the experimental class obtained a score of 4.53 (Strongly Agree), while the control was only 3.63 (Agree). For active engagement, the experiment recorded a score of 4.20 (Agree), well above the controls with 3.17 (Disagree). The perception of material relevance was also higher in the experimental group (4.27) than in the control group (3.27).

On the confidence indicator, the experimental group recorded a score of 3.87 (Agree), while the control group scored 2.93 (Disagree). The motivation to perform was also greater in the experiment (3.97) than in the control (2.87). Overall, the average learning motivation of the experimental students was 4.17 (Agreed), while the controls were only 3.17 (Disagree). These results show that AR-based learning significantly increases student motivation in terms of interest, involvement, perception, confidence, and achievement motivation.

5.7 Student inquiry engagement

The results of observations on student inquiry involvement in the experimental class and the control class are presented in Table 5.

Table 5.

Student inquiry engagement results data

No	Measured Indicators	Experimental Class		Control Class	
		Average Score	Category	Average Score	Category
A	**Formulating the problem**	**3,24**	**Involved**	**2,23**	**Less Involved**
1	Students identify physical phenomena from AR visualizations	3,12	Involved	1,3	Not Involved
2	Students ask questions based on observations of the simulation of teaching materials (waves/forces).	3,5	Highly Involved	2,53	Involved
3	Students are able to formulate problems from initial learning activities.	3,11	Involved	2,85	Involved
B	**Proposing a hypothesis**	**3,53**	**Highly Involved**	**2,79**	**Involved**
1	Students discuss possible causes of a physical phenomenon.	3,6	Highly Involved	2,68	Involved
2	Students convey initial assumptions regarding the relationship between variables (for example the relationship between force and acceleration)	3,55	Highly Involved	3,23	Involved
3	Students demonstrate an understanding of the importance of hypotheses in scientific investigations.	3,44	Involved	2,45	Less Involved
C	**Designing an experiment or activity**	**3,70**	**Highly Involved**	**2,03**	**Less Involved**
1	Students compile work steps or observation procedures using AR.	3,67	Highly Involved	1,32	Not Involved
2	Students select the variables to be observed from the simulation (frequency, amplitude, mass, force).	3,56	Highly Involved	3,24	Involved
3	Students are active in groups when developing exploration scenarios.	3,87	Highly Involved	1,52	Less Involved
D	**Conduct exploration or observation**	**3,77**	**Highly Involved**	**1,35**	**Not Involved**
1	Students use AR applications to observe physical phenomena (reflected waves, interference, friction, etc.)	3,88	Highly Involved	1,15	Not Involved
2	Students record the results of their observations systematicall	3,77	Highly Involved	1,65	Not Involved
3	Students explore virtual objects to test previously made conjectures.	3,65	Highly Involved	1,25	Not Involved
E	**Analyzing Data and Drawing Conclusions**	**3,69**	**Highly Involved**	**2,63**	**Involved**
1	Students compare the simulation results with the initial hypothesis.	3,65	Highly Involved	2,43	Less Involved
2	Students compile scientific explanations based on observation results.	3,58	Highly Involved	2,21	Less Involved
3	Students draw logical conclusions based on available data and visual facts.	3,85	Highly Involved	3,24	Involved
F	**Reflecting on the Process and Results**	**3,80**	**Highly Involved**	**3,19**	**Involved**
1	Students write or convey reflections on the learning process	3,88	Highly Involved	3,54	Involved
2	Students identify errors in the inquiry process	3,76	Highly Involved	2,35	Less Involved
3	Students provide suggestions or improvements for the next activity.	3,76	Highly Involved	3,67	Involved
Average		**3,62**	**Highly Involved**	**2,37**	**Less Involved**

The results showed that Augmented Reality (AR)-based learning models with a multi-interaction approach significantly increased students' inquiry engagement in wave and style materials. The average score of the experimental group reached 3.62 (Highly Engaged), while the control group was only 2.37 (Least Engaged), reflecting the effectiveness of AR in encouraging student active participation.

In the problem formulation indicator, the experimental group achieved a score of 3.24 compared to 2.23 in the control. The score of proposing hypotheses was also higher (3.53 vs. 2.79), indicating a better understanding of the relationships between variables. Notable differences occurred in the indicators of designing experiments (3.70 vs. 2.03) and exploration (3.77 vs. 1.35), indicating that AR aids in more systematic and collaborative observation.

Data analysis and conclusion preparation were better in the experimental group (3.69) than in the control group (2.63), while in the reflection indicator, both were active, but the experiment remained superior (3.80 vs. 3.19). These findings confirm that AR strengthens scientific inquiry, conceptual understanding, and critical thinking skills through contextual and interactive learning experiences.

5.8 Qualitative thematic analysis

5.8.1 Student response

The results of the analysis of semi-structured interview data on students using a thematic approach are presented in Table 6.

Table 6.

Data on student responses to multi-interaction-based AR learning

No	Measured Indicators	Student Response	
		Average Score	Category
A	**The Attraction of Learning**	**3,63**	**Strongly Agree**
1	Learning physics using AR is very interesting and fun	3,68	Strongly Agree
2	3D visualization made me more interested in studying wave material and style	3,54	Strongly Agree
3	I feel enthusiastic every time I use an AR app while studying	3,68	Strongly Agree
B	**Ease of Use of AR Technology**	**3,44**	**Agree**
1	AR apps are easy to use and not confusing	3,35	Agree
2	I had no difficulty accessing and running the AR simulation	3,42	Agree
3	The guidelines for the use of AR in learning are quite clear and helpful	3,56	Strongly Agree
C	**Clarity and Understanding of the Material**	**3,62**	**Strongly Agree**
1	The use of AR makes the concept of waves and styles easier to understand	3,67	Strongly Agree
2	AR simulations help me imagine abstract physical processes	3,47	Strongly Agree
3	I understand the relationship between concepts better after seeing AR simulations.	3,72	Strongly Agree
D	**Engagement and Interaction in Learning**	**3,72**	**Strongly Agree**
1	I am more active in asking questions and discussing when using AR.	3,55	Strongly Agree
2	AR encourages me to be more involved in group learning activities	3,74	Strongly Agree
3	I feel more focused and not easily bored during the learning process.	3,86	Strongly Agree
E	**Benefits to Motivation and Learning Outcomes**	**3,41**	**Agree**
1	Learning with AR makes me more motivated to study physics.	3,46	Strongly Agree
2	I feel more confident in working on the questions after studying with AR.	3,35	Agree
3	I feel like my learning outcomes have improved after using this learning model.	3,42	Agree
F	**Relevance and Implementation**	**3,76**	**Strongly Agree**
1	I feel that this learning is relevant to current technological developments	3,88	Strongly Agree
2	I want to use AR in other subjects as well	3,68	Strongly Agree
3	I feel that this kind of learning will be very useful in the future	3,72	Strongly Agree
	Average	**3,6**	**Strongly Agree**

The results showed that students' response to Augmented Reality (AR)-based physics learning was very positive, with an overall average score of 3.60 (Strongly Agree category). The Learning Attractiveness Indicator recorded the highest score of 3.68, followed by Engagement and Interaction at 3.72, which reflects the high participation of students in questioning, discussing, and group work.

The Clarity and Comprehension Aspect of the Material scored 3.62, indicating that AR is effective in helping students understand abstract concepts such as waves and forces. The ease of use of AR Technology obtained a score of 3.44, indicating the comfort of students in using the application.

Although the Motivation and Learning Outcomes score is slightly lower (3.41), students still feel helped in increasing their confidence and enthusiasm for learning. The highest score was achieved on the Relevance and Implementation indicator (3.76), confirming that students are aware of the importance of AR-based learning in the context of today's technology. Overall, multi-interaction-based AR models are considered to be able to create interesting, relevant, and meaningful learning experiences.

5.9 Teacher's response

The results of the interviews showed that teachers judged the multi-interaction-based AR learning model to be well-suited for abstract physics materials such as waves and forces. This approach is considered to support a wide range of learning styles, is easy to apply, and is flexible for other materials. The guidance on the use of AR is considered clear, although additional technical training is still needed. Teachers also noted improved student understanding and interaction in the classroom. AR technology is considered effective, relevant to the demands of the 21st century, and encourages self-exploration. Most teachers are motivated to use this model because it is supported by adequate school infrastructure and policies.

Interviews reveal that teachers find AR media increases student activity and engagement. One teacher noted, “This media makes students more active, and I feel more enthusiastic in guiding them.” They emphasized that AR helps students grasp abstract concepts like waves and forces through 3D simulations, making learning more concrete, interactive, and engaging. The variety of interactions, exploration, discussion, and reflection also makes lessons more dynamic and less monotonous."

5.10 Development of multi-interaction-based augmented reality (AR) learning models

5.10.1 Development rationale

This model was developed in response to the challenges in learning abstract physics concepts, such as waves and forces. The limitations of conventional media lead to low student understanding, passive learning engagement, and misconceptions. Therefore, the integration of Augmented Reality (AR) and multi-interaction approaches is considered an innovative solution.

5.10.2 Syntax of learning models

Table 7.

Multi-interaction-based AR model syntax

Stages	Main Activities	Types of Interactions
Early Exploration	Students observe physical phenomena through AR applications (waves, forces, etc.).	Visual & Exploratory
Formulating the Problem	Students formulate questions or problems based on the results of observations from the AR simulation.	Reflective & Verbal
Hypothesis Submission	Students suspect the relationship between the variables of the AR phenomenon.	Cognitive and Verbal
Designing Inquiry Activities	Students draw up a plan and choose the variables to be observed from the AR simulation.	Manipulative & Collaborative
Virtual Experiment	Students conduct simulations and record exploration data in AR.	Kinesthetics & Observatif
Data Analysis and Conclusions	Students compare the data with the hypothesis, then draw scientific conclusions.	Reflective & Logical
Reflection and Follow-up	Students and teachers reflect on the learning process and discuss the application of the concept to the real world.	Interpersonal & Advanced Visualization

5.10.3 Model core components

- Learning Media: Android/iOS-based Augmented Reality (AR) apps that can display interactive 3D simulations.
- Learning Scenarios: Using a mini-project-based scientific inquiry approach in groups and project-based problem learning.
- Learning Interactions:

1) Visuals (3D images and animations)
2) Manipulative (exploration of virtual objects)
3) Verbal (discussion and explanation)
4) Reflective (concluding)
5) Collaborative (group work)

- Evaluation: Pretest, posttest, engagement observation, motivational questionnaire, and teacher/student interview.

5.10.4 Adapted theoretical models

1. Constructivist Theory (Vygotsky, Piaget): Meaningful learning occurs when students build their knowledge through direct experience.
2. Cognitive Load Theory: AR reduces cognitive load through concrete visualization.
3. Multimodal Learning Theory: Integration of various learning styles (visual, auditory, kinesthetic) in a single learning ecosystem.

5.10.5 Implications and advantages of multi-interaction-based AR learning models

AR-based learning with a multi-interaction approach offers key advantages for 21st-century physics education. It simplifies abstract concepts like waves and forces through realistic 3D simulations, allowing students to interact with visualized phenomena and deepen their conceptual understanding.

This model not only improves understanding but also boosts student motivation and engagement. By combining visual, experiential, and technological elements, it creates an engaging learning environment that fosters interest, confidence, and active participation. The multi-interaction approach, visual, kinesthetic, reflective, and collaborative, also supports diverse learning styles, ensuring inclusive and effective learning..

Teachers responded positively to the model, noting that AR technology aligns with modern curriculum demands and can be applied across various science topics. It enhanced student interaction, deepened discussions, and encouraged reflection. With adequate infrastructure and training, the model has strong potential for broader adoption, supporting a contextual and interactive learning ecosystem that fosters 21st-century skills like critical thinking, communication, collaboration, and creativity.

6 DISCUSSION

6.1 Improved understanding of physics concepts

The results showed that the AR-based multi-interaction model significantly improved students' understanding of waves and forces. The experimental group achieved higher posttest gains than the control group, with N-Gain values confirming its effectiveness.

These improvements demonstrate that AR with a multi-interaction approach creates a more meaningful learning experience by helping students understand abstract physics concepts through 3D visualization, virtual exploration, and guided reflection. (Delgado-Kloos, 2018; Ozdemir *et al*., 2018; Zhao *et al*., 2023). This model is also effective in reducing misconceptions because students learn through simulation and hands-on interaction (Claudia Wang *et al*., 2023; O'Connor & Mahony, 2023; Zhao *et al*., 2023).

A multi-interaction approach involving visual, manipulative, and collaborative elements has also been shown to support a wide range of student learning styles and is in line with the theory of social constructivism (Bower *et al*., 2014; Wang *et al*., 2021). Thus, multi-interaction-based AR models are an innovative strategy that is feasible to be applied to improve conceptual understanding in modern physics learning.

6.2 Statistical description of posttest results

Descriptive analysis showed a clear difference in posttest scores: the experimental group using AR-based learning averaged 82.50, while the control group scored 69.00. This 13.50-point gap indicates that AR-based learning significantly enhances understanding of wave and force concepts.

The low standard deviation and standard error in both groups showed that the distribution of student scores was relatively homogeneous, so the average obtained could be relied upon as a representation of learning outcomes. This reinforces the belief that these differences in outcomes are influenced by the learning model used, not by individual variations in students' abilities.

These findings are in line with various previous studies that affirm that AR in science learning effectively improves students' cognitive engagement and conceptual understanding through interactive visualization and contextual learning experiences (Delgado-Kloos, 2018; Wang *et al*., 2021; Wen *et al*., 2023). A multi-interaction approach that combines visualization, object manipulation, and collaboration has been shown to be able to build a more complete mental representation of students, especially for abstract concepts such as force and waves (Ozdemir *et al*., 2018; Dou *et al*., 2025).

6.3 Independent t-Test results

The independent sample t-test ($t(58) = 4.791$, $p = 0.000$) showed a significant difference in posttest scores, proving that the AR-based multi-interaction model is statistically more effective than conventional methods in improving students' understanding of physics concepts. This confirms the real cognitive impact of technology-driven learning approaches.

Learning with AR enables students to visualize abstract physics concepts through interactive simulations. The multi-interaction approach, exploration, collaboration, and reflection, promotes active, meaningful learning. (Delgado-Kloos, 2018; Radu *et al*., 2023). AR also strengthens students' ability to connect new knowledge with real phenomena.

These findings are in line with previous studies that showed that the use of AR can reduce misconceptions, strengthen mental representations, and improve conceptual understanding (Gherghel *et al*., 2023). In addition, AR-based learning models provide flexibility to various learning styles of students, making them an effective strategy in modern science education (Ozdemir *et al*., 2018).

6.4 Learning motivation (descriptive analysis and score comparison)

The results showed that AR-based physics learning with a multi-interaction approach significantly boosted students' motivation compared to conventional methods. Experimental group students scored higher across all indicators, interest, engagement, relevance, confidence, and achievement drive, indicating a more engaging and meaningful learning experience.

The use of AR allows students to understand abstract material more visually and interactively, so they are more cognitively and emotionally engaged. This is in line with the results of Delgado-Kloos' (2018) research, which states that AR-based learning is able to increase students' attention, interest, and active participation. 3D visualization and interactive AR simulations enhance students' sense of relevance, boost confidence, and strengthen intrinsic motivation to achieve (Claudia Wang *et al*., 2023).

Overall, these findings support previous studies that AR integration in science learning enhances not only cognitive but also affective aspects, like motivation. The multi-interaction approach, combining visual, manipulative, reflective, and collaborative elements, accommodates diverse learning styles and fosters an engaging, meaningful learning experience (Ozdemir *et al*., 2018).

6.5 Student inquiry engagement

The results showed that the AR-based learning model with a multi-interaction approach significantly enhanced students' inquiry engagement in learning waves and forces. (Cai *et al*., 2023; Wen *et al*., 2023; Al-Masarweh, 2021). Students actively formulated problems, proposed hypotheses, conducted experiments, explored phenomena, and concluded, indicating that AR effectively fosters active, collaborative, and reflective science learning.

These findings align with previous research showing that AR enhances scientific skills and boosts student engagement through interactive visualization and simulation of abstract phenomena. (Reyaz Ahmad Bhat, 2023; Pierson *et al*., 2021; Delgado-Kloos, 2018; Ibanez *et al*., 2014). AR allows students to observe and manipulate virtual objects directly, thus facilitating deeper cognitive engagement in inquiry activities (Claudia Wang *et al*., 2023; Ozdemir *et al*., 2018; Al-Masarweh, 2021). Thus, a multi-interaction approach in AR learning has proven to be effective in building students' scientific thinking skills.

6.6 Student response

The results showed that students responded positively to AR-based physics learning with a multi-interaction approach. They found it more engaging, enjoyable, and helpful in actively understanding abstract concepts like waves and forces through interactive visualization. This is in accordance with the findings of Delgado-Kloos (2018), who stated that AR can increase student interest and engagement through elements of visualization and high interactivity.

In addition, students consider the use of AR technology to be quite easy and relevant to today's technological developments. This positive response reflects that AR-based learning not only motivates, but also strengthens the connection between the material taught and the real life and future of students. Research by Ozdemir *et al*. (2018) and Claudia Wang *et al*. (2023) also shows that AR-based learning can significantly improve learning motivation, perception of material relevance, and student confidence through a contextual and participatory approach.

6.7 Teacher's response

Interview results indicate that teachers consider the AR-based multi-interaction model highly effective for teaching abstract physics concepts like waves and forces. They note that 3D visualization makes complex ideas more concrete, enhances student engagement, supports various learning styles, and fosters independent exploration, aligning well with 21st-century education principles.

These findings are in line with the results of research by Bower *et al*. (2014), which states that AR enables more lively, contextual, and interactive learning, as well as facilitates multisensory learning experiences. In addition, Bacca *et al*. (2014) also noted that teachers tend to be more motivated to use AR technology because of its effectiveness in delivering hard-to-visualize material and its ability to increase student engagement. Despite the need for additional technical training, teachers are still enthusiastic about implementing this model, especially when supported by school policies that favor innovative learning.

7 CONCLUSIONS AND RECOMMENDATIONS

This study confirms that Augmented Reality (AR)-based physics learning using a multi-interaction approach effectively enhances learning quality, particularly on abstract topics like waves and forces. By combining visualization, exploration, reflection, and collaboration, the model improves students' conceptual understanding, motivation, and inquiry participation.

These findings address the limitations of conventional pedagogy in delivering abstract physics concepts and align with previous research on the cognitive benefits of AR. The study highlights the value of multi-interaction as a foundation for personalized and active learning.

Positive teacher responses indicate strong potential for broader adoption, provided that infrastructure and training are in place. Future development should focus on expanding content and teacher capacity, while further research should explore the model’s long-term impact on students’ 21st-century competencies.

REFERENCES

Abdallah, M., Sawalhi, G., Mazhar, A., AlRifaee, M., & Salah, M. (2024). Factors Influencing the Quality of Augmented Reality Applications. *Procedia Computer Science*, *251*, 150–156. https://doi.org/10.1016/j.procs.2024.11.095

Abdullah, N., Baskaran, V. L., Mustafa, Z., Ali, S. R., & Zaini, S. H. (2022). Augmented Reality: The Effect on Students’ Achievement, Satisfaction, and Interest in Science Education. *International Journal of Learning, Teaching and Educational Research*, *21*(5), 326–350. https://doi.org/10.26803/ijlter.21.5.17

Agbo, F. J., Olaleye, S. A., Bower, M., & Oyelere, S. S. (2023). Examining the relationships between students’ perceptions of technology, pedagogy, and cognition: the case of immersive virtual reality mini games to foster computational thinking in higher education. *Smart Learning Environments*, *10*(1), 1–22. https://doi.org/10.1186/s40561-023-00233-1

Al-Ansi, A. M., Jaboob, M., Garad, A., & Al-Ansi, A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Social Sciences and Humanities Open*, *8*(1), 100532. https://doi.org/10.1016/j.ssaho.2023.100532

Al-Masarweh, D. R. Y. (2021). A Review of Augmented Reality in Physics Education and Physics Laboratory Experiments (Applications, Advantages, Challenges). *Turkish Online Journal of Qualitative Inquiry*, *12*(9), 2593–2614. https://www.tojqi.net/journal/article/view/6129

Altinpulluk, H. (2019). Determining the trends of using augmented reality in education between 2006-2016. *Education and Information Technologies*, *24*(2), 1089–1114. https://doi.org/10.1007/s10639-018-9806-3

Alzahrani, N. M. (2020). Augmented reality: A systematic review of its benefits and challenges in e-learning contexts. *Applied Sciences (Switzerland)*, *10*(16). https://doi.org/10.3390/app10165660

Amna Saleem, Huma Kausar, & Farah Deeba. (2021). Social Constructivism: A New Paradigm in Teaching and Learning Environment. *Perennial Journal of History*, *2*(2), 403–421. https://doi.org/10.52700/pjh.v2i2.86

Ansori, I., Arianto, F., & Khotimah, K. (2025). *The Effectiveness of Augmented Reality on Students ' Higher Order Thinking Skills (HOTS) in Geography A Introduction Higher Order Thinking Skills (HOTS) has become a pivotal focus in the Merdeka Curriculum of Indonesia, reflecting the national comm*. *6*(1), 448–464.

Astuti, I. A. D., Wibawa, B., & Siregar, E. (2024). *The Influence of Augmented Reality (AR)-Based Learning Media in Physics Learning: A Systematic Literature Review* (Issue Icliqe). Atlantis Press SARL. https://doi.org/10.2991/978-2-38476-301-6_75

Bacca, J., Baldiris, S., Fabregat, R., Graf, S., & Kinshuk. (2014). Augmented reality trends in education: A systematic review of research and applications. *Educational Technology and Society*, *17*(4), 133–149.

Bizami, N. A., Tasir, Z., & Kew, S. N. (2023). Innovative pedagogical principles and technological tools capabilities for immersive blended learning: a systematic literature review. In *Education and Information Technologies* (Vol. 28, Issue 2). Springer US. https://doi.org/10.1007/s10639-022-11243-w

Bouchey, B., Castek, J., & Thygeson, J. (2021). *Multimodal Learning*. 35–54. https://doi.org/10.1007/978-3-030-58948-6_3

Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented Reality in education - cases, places and potentials. *Educational Media International*, *51*(1), 1–15. https://doi.org/10.1080/09523987.2014.889400

Brannon Barhorst, J., McLean, G., Shah, E., & Mack, R. (2021). Blending the real world and the virtual world: Exploring the role of flow in augmented reality experiences. *Journal of Business Research*, *122*, 423–436. https://doi.org/10.1016/j.jbusres.2020.08.041

Cai, S., Niu, X., Wen, Y., & Li, J. (2023). Interaction analysis of teachers and students in inquiry class learning based on augmented reality by iFIAS and LSA. *Interactive Learning Environments*, *31*(9), 5551–5567. https://doi.org/10.1080/10494820.2021.2012808

Cao, W., & Yu, Z. (2023). The impact of augmented reality on student attitudes, motivation, and learning achievements—a meta-analysis (2016–2023). *Humanities and Social Sciences Communications*, *10*(1), 1–12. https://doi.org/10.1057/s41599-023-01852-2

Cheng, K. H., & Tsai, C. C. (2013). Affordances of Augmented Reality in Science Learning: Suggestions for Future Research. *Journal of Science Education and Technology*, *22*(4), 449–462. https://doi.org/10.1007/s10956-012-9405-9

Claudia Wang, Zhang, M., Sesunan, A., & Yolanda, L. (2023). Peran Teknologi dalam Transformasi Pendidikan di Indonesia. *Kemdikbud*, *4*(2), 1–7.

Cleaver, S., Detrich, R., States, J., & Keyworth, R. (2021). Curriculum Content for Teacher Training (Wing Institute Original Paper). *ResearchGate The Wing Institute*, *June*, 1–30. https://doi.org/10.6084/m9.figshare.14727669

Delgado-kloos, M. I. C. (2018). Augmented reality for science learning: A systematic review. *Computers and Education*, *123*, 109–123.

Dewantara, K. (2015). Pendidikan di Indonesia. *Pendidkan*, *1*(2), 15–32.

Dou, A., Xu, W., & Xu, L. (2025). Interactive Learning Environments: A Systematic Review of Mobile Instant Messaging's Impact, Challenges, and Future Trajectories. *International Journal of E-Collaboration*, *21*(1). https://doi.org/10.4018/IJeC.369815

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*(6), 671–688. https://doi.org/10.1080/09500690305016

Duit, R., Treagust, D. F., & Widodo, A. (2013). Teaching science for conceptual change: Theory and practice. *International Handbook of Research on Conceptual Change*, *March 2017*, 487–503. https://doi.org/10.4324/9780203154472

Fidan, M., & Tuncel, M. (2019). Integrating augmented reality into problem-based learning: The effects on learning achievement and attitude in physics education. *Computers and Education*, *142*(July), 103635. https://doi.org/10.1016/j.compedu.2019.103635

Fitri, U., Amini, R., Zulkarnaini, A. P., & Media, A. (2025). The Use of Augmented Reality in Science Learning To Improve Motivation and Understanding of Science Concepts Among Elementary School Students. *SCIENCE : Jurnal Inovasi Pendidikan Matematika Dan IPA*, *5*(1), 417–424. https://doi.org/10.51878/science.v5i1.4732

Gao, L., Wang, C., & Wu, G. (2024). Wearable Biosensor Smart Glasses Based on Augmented Reality and Eye Tracking. *Sensors*, *24*(20). https://doi.org/10.3390/s24206740

Garzón, J., Pavón, J., & Baldiris, S. (2019). Systematic review and meta-analysis of augmented reality in educational settings. *Virtual Reality*, *23*(4), 447–459. https://doi.org/10.1007/s10055-019-00379-9

Gherghel, C., Yasuda, S., & Kita, Y. (2023). Interaction during online classes fosters engagement with learning and self-directed study, both in the first and second years of the COVID-19 pandemic. *Computers and Education*, *200*(December 2022), 104795. https://doi.org/10.1016/j.compedu.2023.104795

Huang, H. M., & Liaw, S. S. (2018). An analysis of learners' intentions toward virtual reality learning based on constructivist and technology acceptance approaches.

International Review of Research in Open and Distributed Learning, *19*(1), 91–115. https://doi.org/10.19173/irrodl.v19i1.2503

Huang, H. M., Liaw, S. S., & Lai, C. M. (2016). Exploring learner acceptance of the use of virtual reality in medical education: a case study of desktop and projection-based display systems. *Interactive Learning Environments*, *24*(1), 3–19. https://doi.org/10.1080/10494820.2013.817436

Ibanez, M. B., Di-Serio, A., & Delgado-Kloos, C. (2014). Gamification for engaging computer science students in learning activities: A case study. *IEEE Transactions on Learning Technologies*, *7*(3), 291–301. https://doi.org/10.1109/TLT.2014.2329293

Jesionkowska, J., Wild, F., & Deval, Y. (2020). Active learning augmented reality for STEM education—a case study. *Education Sciences*, *10*(8), 1–15. https://doi.org/10.3390/educsci10080198

Joshua Chukwuemeka, E., Abdullateef Eyitayo, B., Hammed Ajani, A., Emeka Joshua, C., Adedeji Hammed, A., & Samaila, D. (2020). A Review of Instructional Models for Effective Teacher Education and Technology Integration. *Sumerian Journal of Education, Linguistics and Literature*, *3*(6), 2617–1732.

Kairu, C. (2021). Augmented Reality and Its Influence on Cognitive Thinking in Learning. *American Journal of Educational Research*, *9*(8), 504–512. https://doi.org/10.12691/education-9-8-6

Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments*, *11*(1). https://doi.org/10.1186/s40561-023-00288-0

Mayer, R. E. (2012). A Cognitive Theory of Multimedia Learning. *Multimedia Learning*, *July*, 41–62. https://doi.org/10.1017/cbo9781139164603.004

Mayer, R. E., & Johnson, C. I. (2008). Revising the Redundancy Principle in Multimedia Learning. *Journal of Educational Psychology*, *100*(2), 380–386. https://doi.org/10.1037/0022-0663.100.2.380

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments: Special issue on interactive learning environments: Contemporary issues and trends. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Mualem, R., & Eylon, B.-S. (2007). "Physics with a Smile"—Explaining Phenomena with a Qualitative Problem-Solving Strategy. *The Physics Teacher*, *45*(3), 158–163. https://doi.org/10.1119/1.2709674

Müller, J. G.-. (n.d.). *Unlocking Augmented Reality Learning Design Based on Evidence From Empirical Cognitive Load Studies: Systematic Literature Review*.

O'Connor, Y., & Mahony, C. (2023). Exploring the impact of augmented reality on student academic self-efficacy in higher education. *Computers in Human Behavior*, *149*(September), 107963. https://doi.org/10.1016/j.chb.2023.107963

Opiyo, E. Z., & Horváth, I. (2010). Towards an interactive spatial product visualisation: A comparative analysis of prevailing 3D visualisation paradigms. In *International*

Journal of Product Development (Vol. 11, Issues 1–2, pp. 6–24). https://doi.org/10.1504/IJPD.2010.032987

Ozdemir, M., Sahin, C., Arcagok, S., & Demir, M. K. (2018). Öğrenme sürecinde artırılmış gerçeklik uygulamalarının etkililiği: Bir meta-analiz çalısması. *Egitim Arastirmalari - Eurasian Journal of Educational Research*, *2018*(74), 165–186. https://doi.org/10.14689/ejer.2018.74.9

Pierson, A. E., Clark, D. B., & Brady, C. E. (2021). Scientific modeling and translanguaging: A multilingual and multimodal approach to support science learning and engagement. *Science Education*, *105*(4), 776–813. https://doi.org/10.1002/sce.21622

Radu, I., Huang, X., Kestin, G., & Schneider, B. (2023). How augmented reality influences student learning and inquiry styles: A study of 1-1 physics remote AR tutoring. *Computers and Education: X Reality*, *2*(November 2022), 100011. https://doi.org/10.1016/j.cexr.2023.100011

Rahmat, A. D., Kuswanto, H., Wilujeng, I., Purwasih, D., Yogyakarta, U. N., & Yogyakarta, U. N. (2024). *The effects of augmented reality technology on learning achievement and attitude toward physics education*. *9*.

Reyaz Ahmad Bhat. (2023). The Impact of Technology Integration on Student Learning Outcomes: A Comparative Study. *International Journal of Social Science, Educational, Economics, Agriculture Research and Technology (IJSET)*, *2*(9), 592–596. https://doi.org/10.54443/ijset.v2i9.218

Robert Maribe Branch. (2009). Approach, Instructional Design: The ADDIE. In *Department of Educational Psychology and Instructional Technology University of Georgia* (Vol. 53, Issue 9).

Rohmah, R. (2017). Miskonsepsi dalam Pembelajaran Sains. *Jurnal Pendidikan Sains*, *5*(1), 45–53.

RYANS, D. G. (1955). Educational psychology. *Annual Review of Psychology*, *6*, 431–454. https://doi.org/10.1146/annurev.ps.06.020155.002243

Saidin, N. F., Halim, N. D. A., & Yahaya, N. (2015). A review of research on augmented reality in education: Advantages and applications. *International Education Studies*, *8*(13), 1–8. https://doi.org/10.5539/ies.v8n13p1

Sesmiyanti, S., Antika, R., & Suharni, S. (2019). *N-Gain Algorithm for Analysis of Basic Reading*. https://doi.org/10.4108/eai.19-7-2019.2289527

Sung, Y. T., Chang, K. E., & Liu, T. C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers and Education*, *94*, 252–275. https://doi.org/10.1016/j.compedu.2015.11.008

Syskowski, S., Wilfinger, S., & Huwer, J. (2024). Impact and Classification of Augmented Reality in Science Experiments in Teaching—A Review. *Education Sciences*, *14*(7). https://doi.org/10.3390/educsci14070760

Tindan, T. N., & Arthur, J. M. (2024). Understanding senior high school students' difficulties in learning physics. *International Journal of Multidisciplinary Research and Growth Evaluation*, *5*(2), 494–498.

Vidak, A., Movre Šapić, I., Mešić, V., & Gomzi, V. (2024). Augmented reality technology in teaching about physics: a systematic review of opportunities and challenges. *European Journal of Physics*, *45*(2). https://doi.org/10.1088/1361-6404/ad0e84

Wang, P., Li, L., Wang, R., Xu, G., & Zhang, J. (2021). Socially-driven multi-interaction attentive group representation learning for group recommendation. *Pattern Recognition Letters*, *145*, 74–80. https://doi.org/10.1016/j.patrec.2021.02.007

Warkentin, M., Altmeyer, K., Liang, Y., Steinmacher, B., Gränz, B., Lichtenberger, A., Küchemann, S., Kuhn, J., & Hoyer, C. (2025). *Hands-on Experiment Supported by Augmented Reality Smartglasses for Learning the Lorentz Force*. 1–20. http://arxiv.org/abs/2502.06421

Waxman, J. B., & Goldie, S. (2009). Create Blueprint Cognitive Theory of Multimedia Learning. *Center for Health Decision Science, Mayer*, 1–4.

Wen, Y., Wu, L., He, S., Ng, N. H. E., Teo, B. C., Looi, C. K., & Cai, Y. (2023). Integrating augmented reality into an inquiry-based learning approach in primary science classrooms. *Educational Technology Research and Development*, *71*(4), 1631–1651. https://doi.org/10.1007/s11423-023-10235-y

Yang, K., Zhou, X., & Radu, I. (2020). *XR-Ed Framework: Designing Instruction-driven and Learner-centered Extended Reality Systems for Education*. http://arxiv.org/abs/2010.13779

Yildirim, O. (2008). Vygotsky's Sociocultural Theory and Dynamics. *Anadolu University Journal of Social Sciences*, *8*(1), 301–308.

Yoon, B. (2021). Toward Equity-Based Pedagogy: Monolingual Teachers' Transformative Thinking Process. *Beijing International Review of Education*, *3*(3), 387–406. https://doi.org/10.1163/25902539-03030010

Yoon, S., Anderson, E., Lin, J., & Elinich, K. (2017). How augmented reality enables conceptual understanding of challenging science content. *Educational Technology and Society*, *20*(1), 156–168.

Zhao, X., Ren, Y., & Cheah, K. S. L. (2023). Leading Virtual Reality (VR) and Augmented Reality (AR) in Education: Bibliometric and Content Analysis From the Web of Science (2018–2022). *SAGE Open*, *13*(3), 1–23. https://doi.org/10.1177/21582440231190821

Authors' Contribution

Both authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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