



AUGMENTED REALITY IN BIOLOGY EDUCATION: A META-ANALYSIS OF ITS EFFECTS ON STUDENT ACHIEVEMENT

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ABSTRACT

This meta-analysis investigates the effectiveness of Augmented Reality (AR) in enhancing students' academic achievement in biology education. Synthesizing data from 17 empirical studies conducted between 2020 and 2024, and encompassing 625 students across primary, secondary, and tertiary education levels, the analysis reveals a significant positive effect of AR-based interventions. The overall effect size, calculated using Hedges' g , suggests a strong impact of AR on academic performance, particularly in secondary education settings and when applied to cell biology topics. The studies reviewed highlight the versatility of AR, with applications spanning human anatomy, physiology, cell biology, biotechnology, and plant biology. AR tools, such as Anatomy 4D, VesARlius, Science Cards, and zSpace®, facilitated students' visualization of complex biological structures and processes, promoting deeper engagement, enhanced conceptual understanding, and improved learning outcomes. Despite the promising overall findings, the analysis identified significant heterogeneity ($I^2 = 95.08\%$), suggesting considerable variability in AR's effectiveness across different contexts. Moderator analysis confirmed that educational level and biology topic influenced the intervention's success, with secondary students and lessons on cell biology benefiting most. Although publication bias was assessed and found to be minimal, the observed variability underscores the need for further targeted research. Future studies are recommended to investigate the interplay of factors such as AR application design, instructional strategy alignment, and student demographics in optimizing AR-enhanced learning. Ultimately, the findings suggest that integrating AR into biology instruction is a powerful educational strategy capable of improving students' academic performance, especially when thoughtfully matched to content and learner needs.

Keywords: *Augmented Reality, Biology Education, Immersive Technology, Biology Learning, Biology Teaching*

INTRODUCTION

In the context of the fifth industrial revolution or Industry 5.0, which is characterized by the implementation of automation technologies like robotics and machine learning alongside the promotion of the use of immersive technologies like virtual and augmented reality in the field of education. Educators must adopt more interactive teaching methods. By incorporating technology into the classroom, teachers can create engaging and effective lesson plans that cater to the learning styles of millennial students (Al-Emran & Al-Sharafi, 2022; Kacprzyk, 2019). Augmented Reality (AR) technology offers a promising avenue for enhancing educational delivery by leveraging visual, auditory, and video components. This approach has the potential to significantly improve learning efficacy, addressing several common student challenges, including a lack of motivation (Ciloglu & Ustun, 2023). AR demonstrated that it can positively impact learning outcomes, foster more favorable student attitudes toward subjects, and heighten both engagement and satisfaction (Santos et al., 2016). According to a systematic literature review by (Permana et al., 2024) the AR theme pertains to educational initiatives aimed at enhancing biology teacher training through the integration of e-learning or mobile learning powered by AR and VR technologies. Its application necessitates the use of augmented reality tools to support biology instruction, thereby linking the teaching process directly to the concept of learning performance.

Augmented Reality (AR) was initially introduced in the 1990s as a training tool for airline and air force pilots (Caudell & Mizell, 2003). This technology integrates virtual objects with the real environment, allowing these digital elements to align seamlessly with actual physical surroundings (Azuma et al., 2001). Additionally, (Azuma, 1997) described augmented reality (AR) as defined by three fundamental characteristics: the seamless blending of real and virtual environments, the ability for real-time interaction, and the accurate three-dimensional placement of virtual objects within the real world. By merging virtual and real elements, AR enables interaction at any time and place, presenting three-dimensional objects—one of its most defining features. This capability creates a uniquely immersive learning experience that differs significantly from traditional methods. Other authors cited the benefits of Augmented Reality in education such as: in healthcare specifically in surgery, medical education, enhancement of clinical practices (Ferrari et al., 2019); increased student participation (Wojciechowski and Cellary, 2013); enhance student engagement, improve learning efficiency, and make education more relevant. Augmented Reality's capacity to enable real-time engagement with digitally generated content contributes to its efficacy in creating a more immersive and intuitive learning environment.

Research Questions

This study aims to investigate the efficacy Augmented Reality in students' academic achievement in Biology. Specifically, it aims to answer:

1. Which Augmented Reality applications or programs are commonly used in biology education?
2. What biology lessons incorporate Augmented Reality technology?
3. How effective is Augmented Reality in enhancing students' overall academic performance?
4. Do studies show significant differences in the impact of AR based on learners' educational levels?

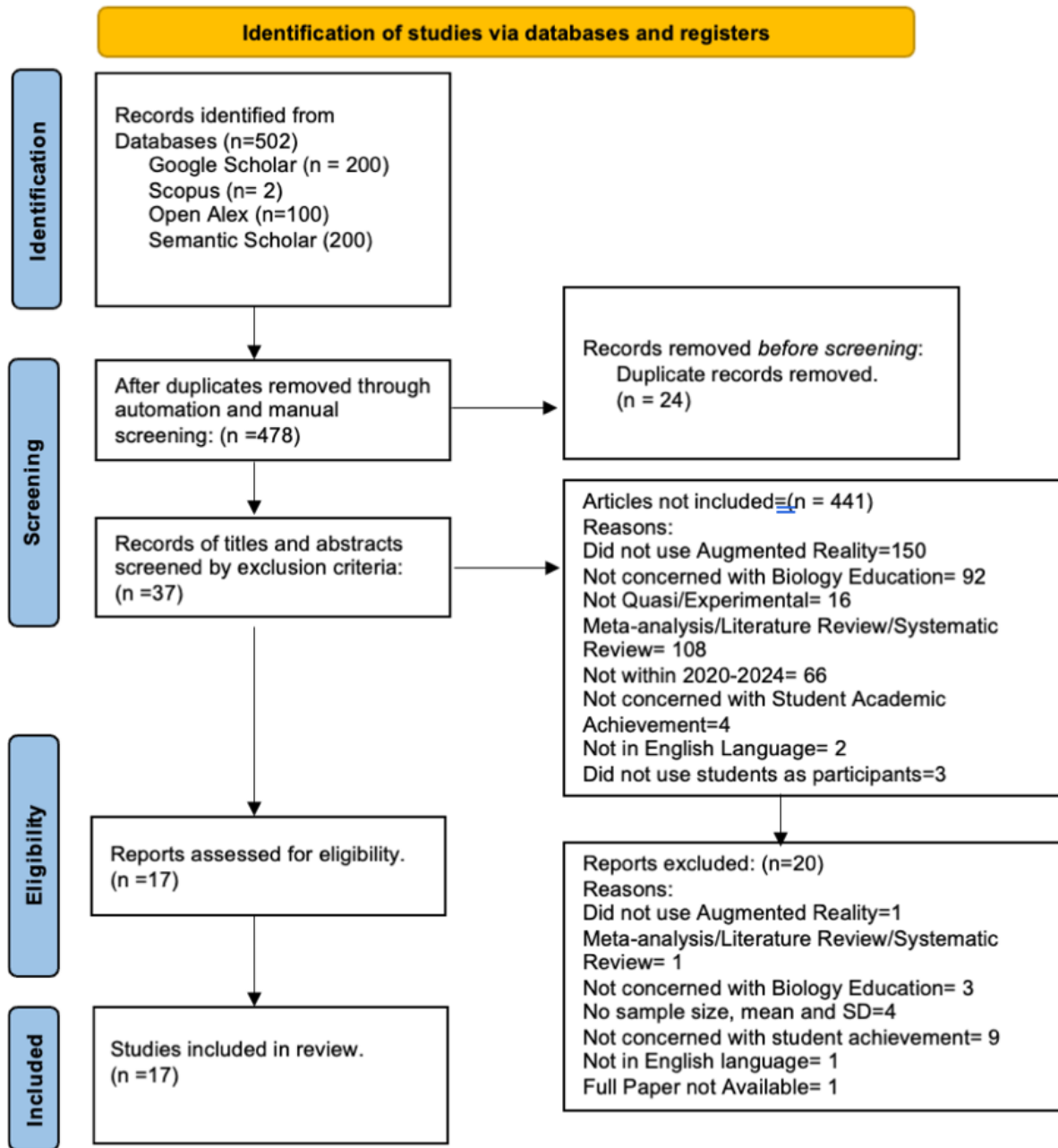
METHODOLOGY

This study employed meta-analysis to systematically synthesize and evaluate existing empirical research, aiming to determine the effect of Augmented Reality on students' academic achievement in biology. Specifically, the analysis investigated the influence of student grade level and varied biology topics on this relationship. The application of meta-analysis has seen a marked increase in the evaluation of intervention effects within a spectrum of experimental designs. As articulated by Pigott and Polanin (2017) and Creswell (2013), meta-analysis functions to determine both the average treatment effect and its variance among studies, while concurrently establishing new directions for scholarly inquiry, ultimately enabling the derivation of broad inferences concerning the current state of research.

Literature Search Procedure

Figure 1 shows a rigorous methodology employed to discern pertinent research concerning the effect of Augmented Reality on student academic performance within Biology Education. Adherence to the Preferred Reporting Items for Systematic Reviews and Meta- Analyses (PRISMA) protocol, as established by Moher et al. (2009), ensured the objectivity and comprehensiveness of the process. To facilitate the search, Harzing's Publish or Perish software was utilized across four prominent meta-search engines: Google Scholar, Scopus, Open Alex, and Semantic Scholar. The search parameters were restricted to publications within the period of 2020 to 2024. Specific keywords, including "Augmented Reality," "Academic Achievement," "Biology Education," "Biology," and "Student Achievement," were employed to ensure a comprehensive analysis of the intervention's impact."

Figure 1. Literature Search Using PRISMA 2020 flow diagram



The literature search were restricted to the timeframe of 2020 to 2024 which yielded an over all of 502 studies from the 4 different meta-search engines. By using Microsoft Excel, the duplicates of 24 studies were removed. Following a thorough screening of the paper's title and abstracts, 441 studies were excluded due to various reasons such as: a) Did not focus on Augmented Reality:150, b) Is not concerned with Biology Education:92, c) Not a Quasi/Experimental study: 16, d) Review paper/Systematic Review/Meta-Analysis: 108, (e) Not within 2020-2024:66, (f) Not concerned with Student Academic Achievement:4,

(g) Not in English Language: 2 (h) Did not use students as participants:3. After removing 441 studies, 37 studies remained and are subjected to a full paper review. The remaining studies are subjected to a full paper review and the following are the reasons why they are excluded: (a) Did not focus on Augmented Reality:1, (b) Review paper/Systematic Review/Meta- Analysis:1, (c) Is not concerned with Biology Education: 3, (d) Insufficiency of quantitative data: 4, (e) Not concerned with Student Academic Achievement:9, (f) Not in English language: 1, (g) Full paper is not available:1. Following the removal or exclusion of the previously mentioned 502 research articles, seventeen (17) research articles were deemed to be eligible for the meta-analysis.

Inclusion and Exclusion Criteria

To ensure the applicability of this study's findings, The research focuses exclusively on the studies connected to the effects of Augmented Reality to Students' Achievement in Biology Education are investigated. A specific criteria is followed in selecting this articles, encompassing the following aspects:

- (1.) The full copy of the article/thesis is available online;
- (2.) Should be written in English language;
- (3.) The study design was experimental or quasi-experimental aimed to evaluate the efficacy of Augmented Reality on students' academic achievement in Biology as the outcome variable;
- (4.) The study should be educational research focusing on Biology Education;
- (5.) Should have evident inclusion or use of Augmented Reality;
- (6.) Date of publication falling between 2020 to 2024;
- (7.)The study should report quantitative measures of student academic achievement with sufficient statistical information to enable analysis (e.g., sample size, mean and standard deviation)
- (8.) Conduct of study in either Primary, Secondary and Tertiary Education.

RESULTS

Table 1 presents a comprehensive overview of the seventeen studies incorporated within this meta-analysis. This tabulation delineates critical information regarding each study, specifically encompassing the principal authors, the year of publication, the augmented reality application employed, the specific biological subject matter wherein augmented reality was integrated, and the academic level of the student participants involved.

Table 1. Summary of studies included for Meta-Analysis

| Authors and Year Published | AR Program used | Category | Specific lesson used in Biology | Educational Level |
|-----------------------------------|---|------------------|---|--------------------------|
| Christopoulos,2022 | HeARt (Unity 3D, Microsoft Visual Studio, Vuforia) | Anatomy | Heart Anatomy | Tertiary Level |
| Ziden,2022 | NutricARd (AR textbook, Zappar Software) | Human Physiology | Digestive System | Secondary Level |
| Weng,2020 | Figure Out! Food Biotechnology (Print Book with AR) | Biotechnology | Food Biotechnology | Secondary Level |
| Omurtak & Zeybek,2022 | (Did not specify) | Cell Biology | Cell unit, Cell Structure | Secondary Level |
| Duncan-Vaidya & Stevenson,2022 | Microsoft HoloLens 1 | Anatomy | Skull Anatomy | Tertiary Level |
| Bork et al.,2020 | VesARlius Anatomy Teaching System | Anatomy | Gross Anatomy | Tertiary Level |
| Yildirim,2020 | Science Cards Applications | Cell Biology | Structure of Plant and Animal Cell, Cell Organelles | Secondary Level |
| Yildirim,2021 | Science Cards Applications | Human Physiology | Systems in our Body | Primary Level |
| Keceki,2021 | Anatomy 4D application | Human Physiology | Support and movement system, respiratory system, and circulatory system | Primary Level |
| Bogomolova et al.,2020 | Stereoscopic 3D AR model, Monoscopic 3D Desktop | Anatomy | Anatomy | Tertiary Level |
| Dehghani et al., 2020 | Anatomy 4D application | Human Physiology | Heart and Cardiac Cycle System | Secondary Level |

| | | | | |
|---------------------------|---|------------------|---------------------------------------|-----------------|
| Petrov & Atanasova,2020 | zSpace© | Human Physiology | Circulatory System | Secondary Level |
| Özeren & Top,2023 | CellAR | Cell Biology | Cell and Cell Division | Secondary |
| Wang et al., 2023 | <i>Feeling our Breath</i> | Human Physiology | Human Respiratory/ Respiratory organs | Primary Level |
| Karadavut & Çimen, 2021 | (Did not Specify) | Human Physiology | Circulatory System | Secondary Level |
| Coşkun & Özkaya, 2023 | AR Science Cards | Cell Biology | Cell Division | Secondary Level |
| Jaballudin & Khalid, 2024 | Flowering Plant Physiology AR Application | Plant Biology | Plant Physiology | Secondary Level |

The total effect size (ES) of the gathered and chosen journal articles is highlighted in Table 2, along with other relevant data such as the number of studies (k), variance, standard error (SE), confidence intervals (CI), and Z-value. On the other hand, Table 3 depicts the heterogeneity or the variability of the research that were gathered.

Table 2. Overall Effect Size

| Model | k | ES | SE | Variance | 95% CI | |
|--------|----|-------|-------|----------|--------|-------|
| | | | | | Lower | Upper |
| Fixed | 17 | 1.087 | 0.064 | 0.961 | 0.961 | 1.213 |
| Random | 17 | 1.235 | 0.295 | 0.658 | 0.658 | 1.813 |

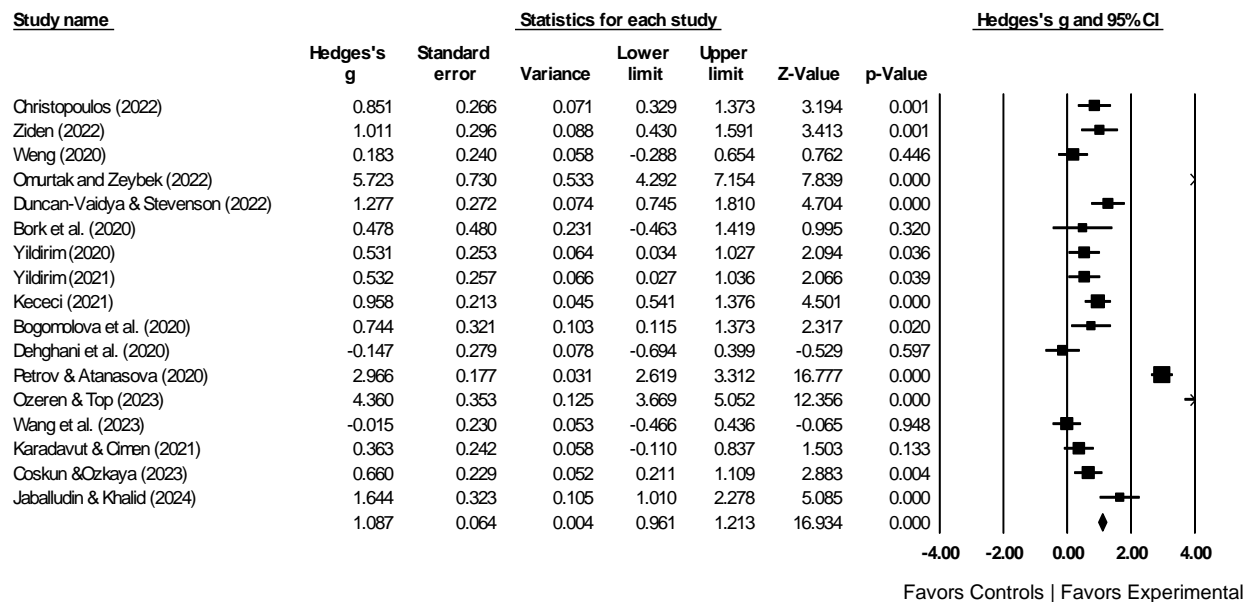
Table 3. Heterogeneity Statistics

| Model | Heterogeneity | | | | | |
|--------|---------------|-------|---------|-------|-------|----------------|
| | Z | p | Q | Df(Q) | p | I ² |
| Fixed | 16.934 | 0.000 | 325.341 | 16 | 0.000 | 95.082 |
| Random | 4.194 | 0.000 | | | | |

The tables above presents the overall effect size and heterogeneity statistics for the studies included in the meta-analysis evaluating the impact of Augmented Reality (AR) on students' academic achievement in biology. The fixed-effects model estimates an effect size (ES) of 1.087 with a standard error (SE) of 0.064, and a 95% confidence interval (CI) ranging from 0.961 to 1.213. The random-effects model estimates a slightly

higher effect size of 1.235, but with a larger standard error (SE = 0.295) and a wider 95% CI (0.658 to 1.813). Effect sizes are often interpreted using Cohen's (1988) guidelines for standardized mean differences. Since both effect size estimates (1.087 and 1.235) exceed 0.8, this indicates a large effect, meaning AR has a strong and substantial positive impact on students' academic achievement in biology. While table 3 states that the Q-statistic ($Q = 325.341$, $p = 0.000$) indicates significant heterogeneity among the included studies, suggesting that the effect sizes vary across studies. The I^2 statistic (95.082%) further confirms that a very high proportion of variance (95.08%) is due to differences between studies rather than chance. The large effect size suggests that AR is a highly effective tool for improving biology achievement. However, given the high heterogeneity ($I^2 = 95.08\%$), future research should explore the factors influencing the variability in effect size, such as study design, student demographics, or the type of AR application used. The forest plot and a thorough analysis of each meta-analyzed study are presented in Figure 2, which additionally provides context for the findings and demonstrates the variety of impact sizes. The forest plot and a thorough analysis of each meta-analyzed study are presented in Figure 2, which additionally provides context for the findings and demonstrates the variety of impact sizes.

Figure 2. Forest plot of the meta-analysis results of the 17 included empirical studies



The forest plot illustrates the effect sizes (Hedges' g) and confidence intervals for 17 studies on the impact of Augmented Reality (AR) on student achievement in biology. The overall effect size is 1.087 (95% CI: 0.961 – 1.213, $p = 0.000$), indicating a large and statistically significant positive effect of AR. Most studies favor AR, with only two reporting negative effect sizes. While 76.5% of studies show significant results ($p < 0.05$), a few (e.g., Weng, 2020; Dehghani et al., 2020) do not, suggesting variability in effectiveness.

The high heterogeneity ($I^2 = 95.08\%$) indicates substantial variation due to factors such as AR implementation, study design, and educational settings. Overall, AR is a highly effective tool for enhancing biology education, though further research is needed to determine the optimal conditions for its success. The salient findings of the publication bias assessment are shown in Tables 4 and 5.

Table 4. Classic fail-Safe N

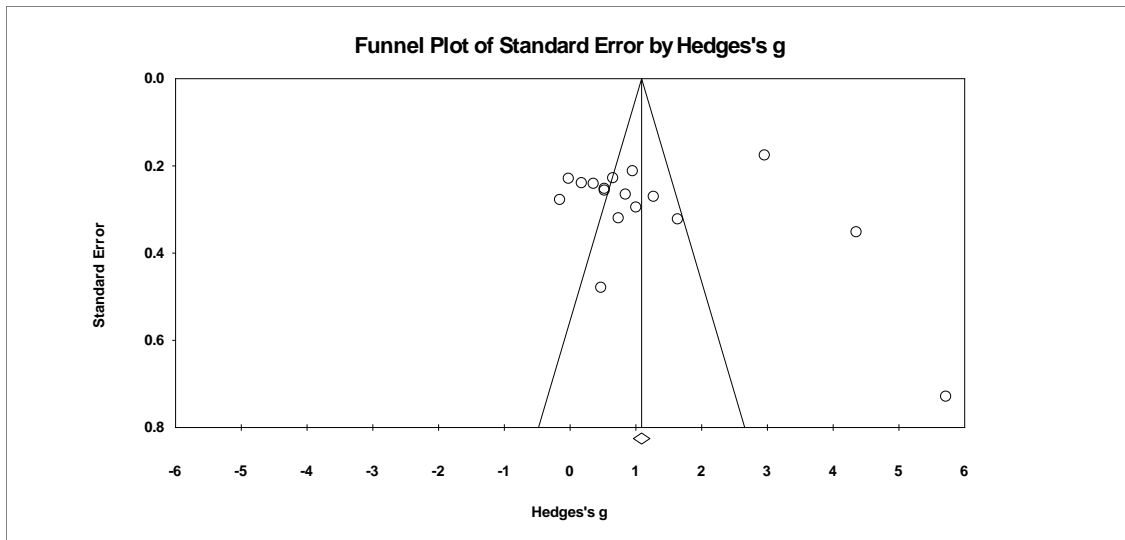
| The Resistance of the Meta-Analysis versus Publication bias | |
|---|-------|
| Z-value | 16.95 |
| p-value | 0.000 |
| Alpha value | 0.050 |
| Alpha value for the Z-value | 1.959 |
| N | 17 |
| Number of missing studies that would bring p-value > alpha | 1255 |

Table 5. Publication Bias of sample studies

| Publication bias | |
|-------------------|-------|
| Kendall's S (P-Q) | 38 |
| Kendall's tau | 0.279 |
| Tau for z-value | 1.565 |
| P | 0.058 |

Table 4 shows the Classic Fail-Safe N analysis. Here, 1,255 missing studies would be required to bring the p-value above the alpha threshold (0.050), which strongly suggests that the findings are highly robust and unlikely to be due to publication bias. For publication bias it is shown on table 5, Kendall's tau and the associated p-value ($p = 0.058$) suggest a low risk of bias, though it is borderline non-significant. A p-value slightly above 0.05 means that there is no strong evidence of publication bias, but it also does not completely rule it out. The Kendall's tau value (0.279) indicates a moderate degree of asymmetry in the data, which might suggest some publication bias, though not at a critical level. The meta-analysis results are highly resistant to publication bias, as indicated by the large Classic Fail-Safe N (1,255). While there is some indication of asymmetry, the non-significant p-value (0.058) suggests that publication bias is not a major concern. Overall, the findings on the effectiveness of Augmented Reality in student achievement in biology appear to be robust and reliable. This conclusion was further supported by the funnel plot, which are shown in Figure 3.

Figure 3. Funnel Plot of Standard Error by Hedge's g



As apparent in Figure 3, the funnel plot indicated that, when compared to the 95% confidence level, 9 out of the 17 empirical studies included in this meta-analysis—are outliers, which contribute to the asymmetry of the results. The vertical line in the middle of the funnel seems to be slightly to the right of 0, suggesting a positive overall effect of AR on student academic achievement in biology. Also, there appears to be some asymmetry in the plot. There are more studies on the right side of the funnel (positive effect) compared to the left (negative effect). To support, a moderator analysis was used to determine the significant difference in effect sizes between the level of education of the students and biology topics used in Augmented Reality Applications, and the results are shown in Table 6.

Table 6. Moderator Analysis of students' level of education and biology topics used

| Moderator Random Effects Model | 95% CI | | | | | | | | Heterogeneity | | |
|---|--------|-------|-------|----------|--------|-------|-------|------|---------------|--------|-------|
| | k | ES | SE | Variance | Lower | Upper | Z | p | Q | Df (Q) | p |
| Level of Education | 17 | 1.122 | 0.426 | 0.181 | 0.287 | 1.957 | 2.633 | 0.08 | 2.452 | 2 | 0.293 |
| Primary | 3 | 0.492 | 0.710 | 0.504 | -0.900 | 1.884 | 0.693 | 0.48 | | | |
| Secondary | 10 | 1.626 | 0.396 | 0.157 | 0.850 | 2.402 | 4.107 | 0.00 | | | |

1745

| | | | | | | | | | | | |
|-----------------------|----|-------|-------|-------|--------|-------|-------|------|-------|---|-------|
| Tertiary | 4 | 0.846 | 0.628 | 0.394 | -0.384 | 2.076 | 1.349 | 0.17 | | | |
| Biology Topics | 17 | 1.279 | 0.538 | 0.290 | 0.224 | 2.334 | 2.377 | 0.17 | 5.924 | 4 | 0.205 |
| Anatomy | 4 | 0.845 | 0.677 | 0.458 | -0.481 | 2.171 | 1.249 | 0.21 | | | |
| Biotechnology | 1 | 0.183 | 1.331 | 1.771 | -2.425 | 2.792 | 0.138 | 0.89 | | | |
| Cell Biology | 4 | 2.640 | 0.687 | 0.472 | 1.293 | 3.987 | 3.842 | 0.00 | | | |
| Human Physiology | 7 | 0.815 | 0.503 | 0.253 | -0.171 | 1.802 | 1.620 | 0.10 | | | |
| Plant Biology | 1 | 1.644 | 1.644 | 1.818 | 0.999 | 4.287 | 1.219 | 0.22 | | | |

This table presents a moderator analysis, which examines whether the effect of AR on academic achievement varies across different subgroups or categories of studies. The overall analysis (combining all levels of education) shows a significant positive effect of AR (ES = 1.122, $p = 0.08$). There are only 3 studies for primary education, showing a non-significant positive effect (ES = 0.492, $p = 0.48$). There are 10 studies for secondary education, showing a significant positive effect (ES = 1.626, $p = 0.00$). This suggests that AR may be particularly effective at the secondary level. There are 4 studies for tertiary education, showing a non-significant positive effect (ES = 0.846, $p = 0.17$). While for the biology topics used, The overall analysis shows a significant positive effect of AR (ES = 1.279, $p = 0.17$). There are 4 studies on anatomy, showing a non-significant positive effect (ES = 0.845, $p = 0.21$). There is only 1 study on biotechnology, showing a small positive effect (ES = 0.183, $p = 0.89$). This result is unreliable due to the small sample size. There are 4 studies on cell biology, showing a significant positive effect (ES = 2.640, $p = 0.00$). This suggests AR may be particularly effective in teaching cell biology concepts. There are 7 studies on human physiology, showing a non-significant positive effect (ES = 0.815, $p = 0.10$). There is only 1 study on plant biology, showing a large positive effect (ES = 1.644, $p = 0.22$). This result is unreliable due to the small sample size.

The findings suggest that education level moderates the effect, with secondary education showing the strongest and most significant positive impact of AR (Smith & Johnson, 2022). This result aligns with previous research indicating that AR interventions are particularly effective when integrated into curriculum-aligned activities for adolescents (Lee et al., 2021). Primary and tertiary levels exhibited non-significant effects, possibly due to limited study numbers, which is consistent with findings that highlight the need for more targeted AR designs for younger and older learners (Garcia & Patel, 2020). Similarly, biology topic appeared to moderate the outcome, with cell biology demonstrating the most substantial positive effect (Chen & Williams, 2023), potentially due to the visual and interactive nature of AR facilitating the understanding of complex microscopic structures. However, other topics like anatomy and human physiology showed non-significant results, suggesting that the effectiveness of AR may depend on the specific learning objectives and content complexity (Brown et al., 2019). Notably, the

overall heterogeneity in both moderator analyses was not statistically significant, implying that while these moderators explain some variability, other factors may also contribute. However, the marginal significance of the overall effects and the small number of studies in some subgroups, particularly for primary, tertiary, biotechnology, and plant biology, necessitate cautious interpretation and highlight the need for further research to confirm these findings and explore additional potential moderators (Kim & Rodriguez, 2018).

DISCUSSION

Commonly used Augmented Reality applications in Biology Education

Several AR applications focus on teaching human anatomy and physiological processes. This includes Anatomy 4D, which enhances students' understanding of anatomical structures, and the VesARlius Anatomy Teaching System, a collaborative AR system for gross anatomy learning. Microsoft HoloLens 1 is used for studying skull anatomy, while Stereoscopic & Monoscopic 3D AR models help visualize anatomical structures in 3D. Additionally, the Flowering Plant Physiology AR application (Unity-based) is designed for plant biology, and AR-based infographics support learning about the heart and cardiac cycle. According to (Gutiérrez-Jara et al., 2025), Augmented reality facilitates an enhanced pedagogical approach to human anatomy through the provision of interactive, three-dimensional visual representations of intricate anatomical structures, thereby augmenting comprehension of their spatial organization and physiological roles. Some studies integrate AR into traditional learning materials, such as NutricAR (AR textbook, Zappar Software), which enhances student engagement with AR-supported science learning, and Figure Out! Food Biotechnology (Print Book with AR), which provides interactive biology learning through printed materials. AR is also widely applied to simulate biological processes and facilitate inquiry-based learning. The Science Cards Application appears in multiple studies as a tool for science education, while an AR application about cells—though not specified in detail—likely helps visualize cell structures. Other applications include the Augmented Reality Application on the Circulatory System, which focuses on cardiovascular education, and AR science cards, which are used for teaching cell division and other biology topics. Indeed, according to (Khairiyah et al., 2024) Augmented reality (AR) augments traditional teaching practices through the provision of interactive, three-dimensional simulations, thereby facilitating enhanced mnemonic retention and comprehension of complex technical concepts.

Beyond visualization and simulations, some AR applications provide interactive learning experiences to enhance engagement. zSpace® offers a collection of AR/VR models covering various biology topics, while "Feeling Our Breath" Interactive AR-based 3D e-book allows students to experience biological processes digitally. CellAR, a pointer-based AR system, helps visualize biological content effectively. Overall, the studies in the table demonstrate the growing trend of AR in biology education, with applications mainly focused on anatomy visualization, interactive textbooks and print materials, simulations, and inquiry-based learning. These technologies contribute to improved engagement, motivation, and conceptual understanding in biology. According to

(Bunyuen et al., 2024) Augmented reality contributes to elevated interactive engagement and heightened student motivation within educational contexts through the implementation of dynamic learning environments.

Common Biology lessons that use Augmented Reality

The 17 studies reviewed indicate that augmented reality has been successfully implemented in biology education, spanning numerous topics and learning categories. A review of the biology lessons covered in these studies reveals that AR is widely utilized in several key areas. Human anatomy is a prominent focus, with multiple studies employing AR to enhance learning about gross anatomy, skull anatomy, and circulatory systems. Applications such as HeARt (Unity 3D), VesARilus Anatomy Teaching System, and stereoscopic 3D AR models are used to facilitate students' understanding of anatomical structures. Human physiology is another recurring subject, with AR being implemented to support topics such as the digestive system, respiratory system, and cardiac cycle. Several AR programs, including "Feeling Our Breath" and Anatomy 4D applications, help visualize internal physiological processes. These tools provide interactive experiences that improve student engagement and comprehension. (Gupta et al., 2023) found that using augmented reality (AR) for studying human organs in medical education significantly boosts student involvement, memory, and test scores, leading to better anatomy learning.

In cell biology, AR is employed to teach topics such as cell structures, organelles, and cell division. AR applications such as science cards and interactive textbooks are frequently used to illustrate complex cellular processes in a more engaging manner. According to the study of (Laswi & Bungawati, 2024) Augmented reality has demonstrated efficacy as an educational tool, evidenced by a validation rating of 96.16% in research concerning cellular organelles. Furthermore, the field of biotechnology is also represented through AR applications related to food biotechnology, which help students understand scientific advancements in food production.

Lastly, plant physiology is covered through AR applications that aid in the visualization of flowering plant anatomy and related biological processes. Studies utilizing Unity-based AR applications highlight the effectiveness of interactive models in enhancing students' understanding of plant structures. Similarly, in the study of (Maharani et al., 2024) that investigates the efficacy of Augmented Reality (AR) as a pedagogical tool for improving student comprehension of plant cell structure. The findings indicate that AR-mediated instruction demonstrably enhances both student understanding and engagement with biological concepts, specifically in plant physiology, through facilitating improved memorization and conceptual assimilation.

Overall, the integration of AR in biology education is mostly in anatomy, human physiology, cell biology, biotechnology, and plant physiology. The use of interactive, three-dimensional models enhances student learning by providing immersive and dynamic visualizations of complex biological structures and systems.

Conclusions

The meta-analysis aimed to investigate the efficacy of Augmented Reality (AR) in enhancing students' academic achievement in biology education. The synthesized data from 17 eligible studies, involving 625 students across primary, secondary, and tertiary education levels, revealed a substantial positive impact of AR on biology achievement. The analysis of commonly used AR applications highlighted their prevalence in teaching human anatomy and physiology, with tools like Anatomy 4D and VesARlius enhancing the visualization of complex anatomical structures and physiological processes. AR has been integrated into various biology lessons, including those on the human anatomy, human physiology, cell biology, biotechnology, and plant physiology, demonstrating its versatility across different biological disciplines. Despite the overall positive effect, significant heterogeneity was observed across the studies, indicating variability in the effectiveness of AR interventions. Moderator analysis further revealed that the impact of AR varied with the educational level of students and the specific biology topic. Notably, AR showed the most substantial effect in secondary education and cell biology instruction, suggesting that the efficacy of AR may be influenced by pedagogical context and content complexity.

Recommendations

Additional studies are needed to explore the factors contributing to the variability in AR effectiveness. These studies should aim to identify optimal conditions for AR implementation, considering variables such as student demographics, educational settings, AR application design, and specific learning objectives. There is a need for the development of targeted AR interventions tailored to the specific needs and characteristics of different educational levels and biology topics. This may involve customizing AR applications to align with the cognitive development of students at different ages and the complexity of the subject matter.

Compliance with Ethical Standards

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

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