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Exploring the Effectiveness of Digital 3D Visualizations in Anatomy Education: A Systematic Review and Meta-Analysis

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ADMINISTRATIVE INFORMATION

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Review Stage at time of this submission - Data analysis.

Conflicts of interest - None declared.

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Amendments - This protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) on 15 January 2025 and was last updated on 15 January 2025.

INTRODUCTION

Review question / Objective Objectives: 1. Quantitative Evaluation of Effectiveness: To quantitatively assess the overall impact of digital 3D visualizations compared to traditional 2D methods on spatial reasoning, anatomy knowledge, learning engagement, and retention among undergraduate students in anatomy education.
2. Exploration of Moderators: To investigate how student-specific characteristics (e.g., spatial ability, prior exposure to 3D tools) and visualization types (e.g., animated vs. interactive 3D) moderate the effectiveness of digital 3D tools in anatomy learning.
3. Comparative Assessment of Visualization Techniques: To compare the differential impacts of animated 3D and interactive 3D visualizations on spatial reasoning, knowledge retention, satisfaction, and learning engagement.
4. Guidance Role: To examine the extent to which the presence of guidance (e.g., instructor-led vs. self-directed) impacts the effectiveness of digital 3D visualizations in anatomy education.

Research Questions (RQ):
1. What is the overall effect of digital 3D visualizations compared to traditional 2D methods on spatial reasoning, anatomy knowledge, engagement, and retention in anatomy education?
2. How do student characteristics (e.g., spatial ability, prior exposure to 3D tools, and education level) and visualization types (e.g., animated 3D vs. interactive 3D) influence the effectiveness of digital 3D visualizations?
3. How do animated 3D visualizations yield different learning outcomes compared to interactive 3D visualizations, particularly for spatial reasoning, learning satisfaction, and knowledge retention?

Rationale The integration of technology in anatomy education aligns with the broader global shift toward Technology-Enhanced Learning (TEL). Yet, educators and researchers face challenges in

optimizing these tools to meet the diverse needs of students. By expanding a systematic literature review (SLR) into a systematic literature review and meta-analysis (SLR-Meta), this study seeks to quantitatively evaluate the impact of digital 3D visualizations and explore factors that moderate their effectiveness.

Condition being studied Technological advancements have transformed traditional teaching methods in anatomy education, with digital 3D visualizations emerging as a promising tool. These visualizations provide learners with an interactive, immersive, and spatially rich experience, facilitating the comprehension of complex anatomical structures. However, despite their growing popularity, questions remain about the true effectiveness of 3D tools compared to traditional 2D methods, particularly in improving spatial reasoning, anatomy knowledge, and learner engagement.

METHODS

Search strategy Search Strategy (PRISMA):
A comprehensive search was conducted in PubMed, Scopus, and Web of Science to identify studies published between 2000 and 2023. Search terms included '3D visualizations,' 'anatomy education,' and 'spatial ability,' combined with Boolean operators. Titles and abstracts were screened for relevance, followed by a full-text review using predefined inclusion criteria.

PICO Framework:
The research questions were structured using the PICO framework. Undergraduate anatomy students served as the target population (P), with digital 3D visualizations (I) compared against traditional 2D methods (C). Outcomes (O) included measures of spatial reasoning, anatomy knowledge, and engagement. Data were extracted systematically, ensuring consistency with PICO-defined variables."

Participant or population The participants in the studies selected are undergraduate medical students.

Intervention The intervention tool is a digital 3D learning tool with digital 2D cross sections, digital 3D, and videos.

Comparator The interventions compared 2D vs 3D and 3D dynamic vs 3D statics as intervention tools.

Study designs to be included All included studies are designed to compare digital media interventions.

Eligibility criteria
Inclusion Criteria:
1. Studies must compare digital 3D visualizations to traditional 2D methods in anatomy education.
2. The population must include undergraduate or preclinical students enrolled in anatomy courses.
3. Studies must report outcomes relevant to spatial reasoning, anatomy knowledge, learning engagement, or knowledge retention.
4. Only peer-reviewed journal articles published in English are included to ensure quality and accessibility.
5. Studies employing quantitative methods and providing sufficient data for calculating effect sizes were prioritized for meta-analysis.

Exclusion Criteria:
1. Studies that focus solely on user satisfaction or technological usability without measuring learning outcomes are excluded.
2. Non-comparative studies, such as those evaluating only a single instructional method, are not included.
3. Conference abstracts, review papers, and gray literature (e.g., theses, and technical reports) are excluded due to the limited data available for extraction.
4. Studies involving participants outside the undergraduate student population, such as postgraduate professionals or high school students, were excluded to maintain focus on higher education.
5. Non-English articles were excluded due to resource constraints in translation and verification.

Information sources
Electronic Databases:
PubMed: For biomedical and life sciences literature, focusing on anatomy education and related interventions.
Scopus: For a comprehensive interdisciplinary collection of research articles.
Web of Science: For high-quality peer-reviewed articles across multiple disciplines.
ERIC (Education Resources Information Center): For educational research, particularly related to instructional tools and learning outcomes.

Manual Search:
Snowballing technique
Reference Lists: Screening the bibliographies of included studies for additional relevant articles.
Cited References: Backward and forward citation tracking using tools like Google Scholar.

Main outcome(s) The study is expected to yield insights across the following primary and secondary outcomes:
Primary Outcomes
1. Spatial thinking: Improvement in students' ability to visualize, manipulate, and interpret anatomical structures in 3D
space. Measured through spatial ability tests (e.g., mental rotation tasks).
2. Anatomy Knowledge: Enhanced understanding and retention of anatomical structures, relationships, and
functions. Typically measured via post-tests, quizzes, or practical exams.
3. Learning Engagement: Increased motivation and active participation during anatomy
lessons. Assessed through surveys, self-reports, or observational measures.

Secondary Outcomes
1. Knowledge Retention: Long-term recall and application of anatomical knowledge over extended periods (e.g., weeks or months after intervention).
2. Learning Satisfaction: Positive perceptions of the learning experience using 3D visualizations. Evaluated through self-reported satisfaction surveys or focus group feedback.
3. Cognitive Load: Reduction in cognitive effort required to comprehend anatomical structures. Measured through validated cognitive load scales or task performance efficiency.
4. Task Performance: Improved accuracy and efficiency in tasks requiring anatomical knowledge (e.g., identifying structures and reconstructing relationships).

Additional outcome(s)
Expected Trends
1. 3D visualizations are predicted to show superior outcomes for spatial reasoning, engagement, and knowledge retention compared to 2D methods.
2. Interactive 3D tools may outperform static or animated 3D visualizations due to their manipulability and user-centered design.
3. Students with high spatial ability may exhibit more significant gains, but low spatial ability students are expected to benefit most from guided interventions.

Data management Data is stored using the 3:2:1 protocol. Only authors can view the data and its analysis. As we are reviewing published studies, the identities of the participants are protected.

Quality assessment / Risk of bias analysis The quality of assessment is done using SIGN50 and the Kirkpatrick model. The risk of publication bias is calculated in the meta-analysis.

Strategy of data synthesis The results will be synthesized using a systematic literature review narrative approach, discussing the quantitative findings of the meta-analysis.

Subgroup analysis To analyze the subgroups, we hypothesize the following:
1. Interactive 3D visualizations yield greater improvements in spatial reasoning than animated 3D visualizations.
2. Guided interventions outperform unguided interventions for students with low spatial ability.
3. High spatial ability students show significant gains regardless of guidance or visualization type.

Sensitivity analysis This will be done to:
1. To ensure that the results are not unduly influenced by specific studies, methodological decisions, or statistical assumptions.
2. Identify the impact of variations in study quality, sample sizes, or effect sizes on the overall conclusions.

The results will be reported in the "Results" and "Discussion" chapters of the article.

Language restriction Only studies in English will be selected.

Country(ies) involved Authors are from Jamaica and Estonia.

Keywords Digital 3D Visualizations, Spatial Thinking, Anatomy Education, Anatomical Understanding, Guided Learning.

Dissemination plans The article will be published as open access to allow for quick availability of the findings.

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