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Collaborative Extended Reality Simulation in Healthcare Education: A Systematic Review and Meta-analysis

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Abstract. This study aims to synthesize the educational effects of collaborative extended reality (XR) simulations in healthcare education and to identify design features and collaboration structures that enhance their effectiveness. Building on prior meta-analyses showing that simulation-based learning is effective for complex cognitive and technical skills, that VR-based education can improve knowledge and skills compared with traditional or other digital instruction, and that interprofessional simulation enhances teamwork, communication, and collaborative attitudes, this study addresses the gap that these strands of research have rarely examined XR-based team simulations as a distinct object of analysis. Using a systematic review and meta-analytic approach guided by PRISMA, the study included randomized and quasi-experimental studies in which two or more health professions learners interact simultaneously in VR/AR/MR environments with comparison conditions. The meta-analysis of 11 independent studies (41 effect sizes) revealed a large overall effect size (Hedges' $g = 0.819$, $p < .001$), confirming that collaborative XR simulations are significantly more effective. Furthermore, the study will identify whether effectiveness differs by collaboration structure and XR design features to provide evidence-based design principles for the iLRN iLEAD track.

Keywords: Collaborative Extended Reality Simulation, Healthcare Education, Systematic Review, Meta-Analysis.

1 Introduction

In fields such as health professions education and medical education, where repeated clinical practice in real-world settings is required, it is difficult to provide sufficient clinical practice due to constraints related to cost, safety, and ethical issues. As a way to address these practical challenges, simulation-based learning has been continuously utilized. In other words, simulation-based learning has been emphasized as one of the effective teaching–learning strategies because it allows learners to repeatedly conduct clinical practice in contexts similar to real situations in a relatively safe and low-cost manner [1]. The results of meta-analyses on simulation-based learning [1] show that simulation-based learning has particularly large effects in domains that require complex technical and cognitive skills, and that specific instructional design elements such as scaffolding and feedback can further enhance these effects [1].

Educational effects similar to those of simulation-based learning have also been reported in XR media environments that include VR and AR. Systematic reviews and meta-analyses in health and medical education report that VR education can contribute more to improving learners' cognitive and technical competencies than general digital education or traditional education [5]. However, these systematic reviews and meta-analyses also point out several limitations, such as substantial heterogeneity in research designs and outcome measures among the included studies and the difficulty of examining long-term learning outcomes [3]. In addition, scoping review studies on VR education indicate that, although VR- or XR-based education can improve cognitive and technical aspects, there is a lack of concrete instructional design and assessment guidelines, which is identified as a limitation [2].

Meanwhile, in health and medical education, interprofessional simulation-based education, which enables learners to acquire competencies related to communication, role understanding, and teamwork required in real clinical settings, has been highlighted [6]. According to meta-analytic results, interprofessional simulation-based education produces statistically significant, moderate-level improvements in communication and teamwork-related competencies compared to traditional education [6]. Furthermore, simulation-based interprofessional education has been shown to lead to more positive attitudes and perceptions toward collaboration [7].

Taken together, numerous previous studies report that simulation-based learning, XR- and VR-based learning, and interprofessional simulation can yield effective educational outcomes, particularly in education that requires clinical practice [1, 6]. However, comprehensive studies such as systematic reviews that analyze the educational effects of collaborative XR simulations by treating simulation, XR and VR technologies, and team-based collaborative learning as the main unit of analysis are still limited. In particular, meta-analyses that can derive more objective results based on quantitative effect sizes have not yet been sufficiently conducted.

2 Research Gap & Purpose

Systematic reviews and meta-analyses of simulation-based education and XR-based education have reported positive outcomes of these educational approaches, but they share several limitations. First, in simulation-based learning, instructional design-related factors such as learners' prior knowledge, scaffolding, and technological fidelity can influence educational outcomes, yet these factors have not been adequately considered in systematic reviews and meta-analyses, and thus effective instructional design elements have not been sufficiently accumulated [1]. Furthermore, systematic reviews, meta-analyses, and scoping reviews on VR- and XR-based education show substantial heterogeneity in learning outcome measures and learner characteristics across studies, and discussions of practically applicable elements such as instructional design and assessment strategies are also insufficient [5]. In addition, because most studies have conducted only narrow-range subgroup analyses, it is difficult to determine which XR instructional designs have positive impacts on learning outcomes [3].

Moreover, systematic reviews and meta-analyses on interprofessional education have confirmed positive effects on collaborative learning and communication, but they often group heterogeneous simulation types into a single category, making it difficult to precisely identify the unique impact of XR-based collaborative simulations [6]. In addition, these studies mainly focus on the level of individual or team performance rather than on collaborative learning itself. Although they address aspects such as interprofessional versus single-discipline groups, explicit role assignment, and single-user versus multiuser XR, there is still a lack of quantitative comparative studies that consider key XR design elements in an integrated way [1].

Recently, in health and medical education, there has been an increase in empirical studies that employ VR- and XR-based collaborative simulations to target competencies such as communication, situation awareness, and teamwork. However, meta-analyses that focus exclusively on collaborative simulations and quantitatively investigate differences in effects according to XR design elements and collaboration structures have rarely been conducted. In other words, there is a lack of meta-analytic research that objectively and systematically verifies the educational effects of collaborative XR simulations and derives effective instructional design elements and guidelines.

Therefore, this study aims to identify the educational value and effects of collaborative XR simulations in healthcare education using systematic review and meta-analytic methods. To clarify the relationship between XR design elements and learning effects, this study established a mapping framework based on the Input-Process-Output (IPO) model. Table 1 illustrates how specific XR features facilitate collaborative learning mechanisms and lead to diverse educational outcomes in healthcare.

Table 1. Mapping of XR Design Features, Learning Mechanisms, and Outcomes.

Design Feature (Input)	Learning Mechanism (Process)	Educational Outcomes (Output)
Immersion Level (VR/AR/MR)	Psychological Fidelity & Presence	Knowledge & Technical Skills
Multi-user Interaction	Shared Mental Models	Teamwork & Communication
Role-based Scripting	Interprofessional Interaction	Collaborative Attitudes
Real-time Feedback	Reflective Practice	Situation Awarenes

To achieve this research purpose, the following research questions were established:

- RQ1: What is the overall effect size of education utilizing collaborative XR simulation?
- RQ2: What are the moderating variables that can specifically verify the educational effectiveness of collaborative XR simulation, and what differences in educational effectiveness exist according to these variables?

3 Methods

This study was conducted as a systematic review and meta-analysis based on the PRISMA guidelines [4]. The literature search methods, study selection procedures, inclusion and exclusion criteria, search strategy, data extraction methods, and data analysis methods were clearly specified to ensure transparency of the research.

3.1 Selection Process and Inclusion Criteria

This study established healthcare, extended reality (XR), and collaborative learning as the primary inclusion criteria, and the selection and exclusion process were conducted according to the stages of the PRISMA flowchart.

First, in the Identification stage, a total of 2,255 records were identified through the Scopus, PubMed, and citation platforms. After removing duplicates, 2,137 records were secured.

In the Screening stage, titles and abstracts were reviewed to exclude studies that were not related to healthcare or XR, as well as publication types such as reviews and meta-analyses. This process resulted in the selection of 131 abstracts, and records with no collaborative element or inappropriate populations and interventions were further excluded.

In the Eligibility stage, the full texts of the 44 selected articles were assessed in depth. During this stage, studies were ultimately excluded if they had no quantitative data for meta-analysis, were not a collaborative design, or were single-group pre-post studies. Through this rigorous process, a final total of 11 studies were ultimately included in the quantitative synthesis (meta-analysis).

3.2 Study Selection and Coding Reliability

To ensure reliability in the study selection and coding process, three independent reviewers screened the titles and abstracts of identified records and subsequently assessed full-text articles for eligibility according to the predefined inclusion criteria. Disagreements between reviewers were resolved through discussion.

For the coding of study characteristics and outcome variables, the reviewers independently coded a subset of studies. Interrater reliability was assessed using Fleiss's kappa coefficient. A kappa value above .75 was considered acceptable. After achieving satisfactory reliability, the remaining studies were coded according to the established coding scheme.

To systematically analyze the characteristics of collaborative XR simulations, the included studies were coded based on the following criteria: Immersion Level was categorized into Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) based on the display technology and the degree of environmental integration. Collaboration Structure was coded into Interprofessional Education (IPE), where learners from two or more health professions interact, and Single-disciplinary Education.

3.3 Data Analysis

The quantitative synthesis was conducted using a meta-analytic approach to estimate the overall effectiveness of collaborative XR simulations in healthcare education (RQ1). For each included study, standardized mean differences were calculated as the effect size metric. Because many primary studies were expected to involve relatively small sample sizes, Hedges' g was used as the primary effect size index to correct for small-sample bias. A random-effects model was employed to pool effect sizes, as variability across studies was expected due to differences in learner populations, XR technologies, simulation designs, and outcome measures. This model assumes that the true effect size may vary across studies and therefore provides a more conservative and generalizable estimate. Statistical heterogeneity among studies was assessed using Cochran's Q statistic and the I^2 index. The I^2 statistic was interpreted using commonly accepted thresholds.

To address RQ2, subgroup analyses will be conducted to explore the moderating variables that can specifically verify the educational effectiveness and to analyze the differences in effectiveness according to these variables. To evaluate the potential influence of publication bias, visual inspection of funnel plots was conducted, and statistical tests such as Egger's regression test were applied when a sufficient number of studies are available. In addition, the trim-and-fill method was used to estimate the potential impact of missing studies on the overall effect size. To examine the robustness of the meta-analytic findings, sensitivity analyses were performed using a leave-one-out procedure, in which the overall effect size was recalculated after sequentially removing each study. This approach helps identify influential studies and evaluate the stability of the results. All statistical analyses were conducted using Comprehensive Meta-Analysis (CMA) software.

4 Results

A random-effects meta-analysis of 41 effect sizes derived from 11 independent studies revealed a statistically significant overall effect (Hedges' $g = 0.819$, $SE = 0.067$, 95% $CI = 0.687–0.951$, $p < .001$). This indicates a large positive effect of the intervention across the included studies. The prediction interval ranged from 0.129 to 1.509, suggesting that future studies are also likely to observe positive effects. Statistical heterogeneity was assessed to ensure the robustness of the findings.

5 Conclusion

This study focuses not on comprehensive XR simulation-based learning but specifically on collaborative XR simulation-based learning as the sole object of analysis and seeks to contribute to the field of collaborative XR-based learning research by identifying educational effects in health and medical education more objectively and quantitatively. In particular, unlike previous meta-analyses that have separately examined simulation-based learning, VR- and XR-based education, and interprofessional simulation-based learning [1, 6], this study centers on a form of education in which XR technologies, including VR, are combined with collaborative simulation-based learning.

The present study employed a random-effects meta-analysis and confirmed that collaborative XR simulation in healthcare education yields a statistically significant and large positive overall effect on learning (Hedges' $g = 0.819$, $p < .001$) (RQ1). This suggests that collaborative XR simulation can make a meaningful positive contribution to enhancing learners' experiences and outcomes in healthcare education. While the current findings establish a robust overall effect size, they also point to the need for further investigation into what moderating variables can specifically verify the educational effectiveness and what differences in effectiveness exist according to these variables (RQ2). Therefore, beyond simply estimating effect sizes, the findings of this study provide a theoretical foundation for developing future design approaches to collaborative XR simulation-based learning.

Finally, this study has significance in that it does not confine itself to XR technologies alone but expands the discussion to the design, implementation, and evaluation of immersive learning, thereby aligning with the perspective of immersive learning education and design pursued by the iLRN iLEAD track. In addition, by deriving and supplementing evidence related to design, implementation, and evaluation identified in VR and XR implementation studies and interprofessional simulation research [6], the study serves as a resource for curriculum design, design-based research, and future studies in collaborative XR simulation-based education.

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