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Effectiveness of Simulation-Based Activities vs. Traditional Interventions in Teaching Biology: A Meta-Analysis

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ABSTRACT

One of the emerging educational technologies is simulation-based activities.Numerous research has been conducted to compare virtual reality to various techniques of teaching anatomy, including structures, lectures, graphical representations, and mixed training.This meta-analysis was focused on the effectiveness of simulation-based activities in teaching biology vs. the traditional interventions in teaching biology. The scope was limited to interventions involving simulations in biology for High school and Senior High School students in STEM contexts. This systematic review showed that when compared with conventional or digital teaching methods, simulation-based activities can enhance the effectiveness of teaching and learning biology. Of all the 15 studies, five evaluated the satisfaction level as a secondary outcome, which shows that most students were more interested in using simulation-based activities to learn biology. Thus, simulation-based activities as an intervention could enhance the quality of teaching biology.Due to the lack of qualitative and descriptive data, the risk of bias for most studies wasuncertain. On the contrary, the researcher emphasized that the meta-analysis results are not concise due to the lack of standardized procedures and high heterogeneity of the studies and subgroups.
Keywords: Simulation-based activities, Home-based Activities, Meta-analysis

INTRODUCTION

As schools adjust to the new norm of remote instruction, educators—particularly biology teachers—need innovative methods to maintainstudents' engagement. One way to address this issue is to use simulation-based activities in teaching. Biology is a graphic science thought of as an essential foundation for scientific learning. In a biology class, the learners identify morphology, anatomical structures, and spatial relationships. Nevertheless, biology students often experience challenges acquiring an adequate understanding of three-dimensional anatomy from pictures, such as those in journals, textbooks, printouts, and PowerPoint (Yammine, 2016).So, it has become essential to develop modern strategies concentrated on efficient and high-quality biology education and learning.

The use of simulation-based activities (SBAs) in biology teaching has become a favorite over the last few years (Sugand, 2010). Remarkably, virtual simulation is a technology that allows discovering and manipulating computer-generated multimedia situationsor environments in realtime. It allows for an active learning experience through different levels of engagement. The increase of virtual simulations could be traced back to the 1960s in the entertainment industry. Simulationspromise to deliver more immersive, meaningful experiences, with applications in many domains, including shopping, entertainment, training, and education (Hu-Au,2017). Programmers have created enthralling experiences that let users go within their bodies' cells, explore the Solar System, and come face to face with recreations of epic conflicts from history. Virtual reality technologies were extensively employed for flight simulator training and exercises (Hawkins, 1995).The increasing attention in simulation-based activities has been attributed to integrating technology inthe science educational world, particularly for teaching and learning biology(Pilot, 2018). Simulation-based activities immerse students in a virtual environment that enables them to understand complex 3D anatomic linkages swiftly. Numerous research has been conducted to compare virtual reality to various techniques of teaching anatomy, including structures, lectures, graphical representations, and mixed training.Considering these benefits, it is commonly believed that incorporating simulation-based activities into classroom instruction might increase student learning. Numerous studies of the literature (e.g., Scalise et al., 2011; Smetana and Bell, 2012) evaluated whether and how simulations to aid in the augmentation of student learning.However, this body of knowledge has not been objectively and systematically studied to ascertain if simulations influence student learning.Consequently, the objective of this systematic review was to explore the educational effectiveness of simulation-based activities when applied to biology teaching in comparison with conventional or 2D digital methods in the class. Three research questions guided this study:

1) Are the students'test scores improvedusing simulation-based activities compared to the other teaching methods?
(2) Are the satisfaction levels higher in simulation-based activities thanother teaching methods?
(3) Do the learning topics, intervention, and comparator play a regulating role in the distinction?

METHODS

Scope

This meta-analysis is focused on the effectiveness of simulation-based activities in teaching biology. The scope was limited to interventions involving simulations in biology for High school and Senior High School students in STEM contexts. The analysis only included studies with participants in the K–12 grade range, although interventions did not need to occur in a formal school setting. Therefore, the results will be applied directly to simulation and curriculum designers working in these grade levels. The list of possible consequence measures was kept comprehensive at this point in the search process to be responsive to the literature.

Search Strategy

The researcher used the software - Harzing's Publish and Perish from the (https://harzing.com). This software is used inthe retrieval and analysisof academic citations. The researcher also used the three well-known and comprehensive databases to ensure the search covered all the relevant literature and journals: the Crossref, SCOPUS, and Web of Science. To identify as many articles as possible, the researchersearched the title, abstract, and keyword or descriptor fields in the software. The researcher decided to keep the search terms relatively broad to capture many potential articles but not too wide to overload the process. Specifically, the researcher used the combination of the term's simulation or computer simulation along with STEM content terms such as science education and biology teaching. Searching for simulation alone would have produced an order of magnitude more articles than the actual search conducted. Reviewing such a large volume of essays wouldhave taken a prohibitively long time to sort through, given our resource constraints properly.

Inclusion and exclusion criteria

The researcher included randomized controlled studies comparing and studying simulation-based interventions with control methods in teaching biology. In this meta-analysis, the simulation-based activities, including interactive 3D models, virtual biological structures, and simulation-based games, could be performed as a single intervention or blended with others [Fernandez, 2017]. SBAs as an intervention for science education can be displayed with various tools, including computer and mobile device screens. Some studies were excluded for the followingreasons: not randomized controlled study; not in the fieldof biology teaching; absence of an intervention; lackof test scores; insufficient data for effect size calculation. The publication date of the detailed studies was limited from 2015-2020.

Heterogeneity Test and Data Synthesis

All analyses were conducted by "Meta-Essentials" (Suurmond et al., 2017). Comparators included conventional education and other types of digital-based activities. The researcher gathered standardized mean differences (SMDs) and associated 95% confidence intervals (CIs) for test scores and satisfaction levels across experiments.The researcher could not come up with a compelling explanation for SMDs in various types of simulation-based activity programs. As a result, the effect size was estimated using the Cohen rules: 0.2 (no impact), 0.2 to 0.5 (little effect), 0.5 to 0.8 (moderate effect), and > 0.80 (big effect) (Landis, 2017). The researcher used the I2 statistic to measure heterogeneity; I2 values of less than 25% (low), 25 to 75% (medium), and greater than 75% (high) show varying degrees of heterogeneity (Higgins, 2003). If there was no heterogeneity (I2 > 50%), the fixed-effect model was used to pool data; otherwise, the random effect model was employed (I2 50%). When subgroup analysis was considered required, it was undertaken. Three characteristics of each random controlled study were identified as potential moderators: the learning topic, the intervention, and the comparator. Sensitivity tests were performed to ascertain whether the results of individual studies significantly influenced the outcomes of meta-analyses (Cong et al., 2017). A funnel plot and Begg's test were utilized to establish publication bias. A p-value of 0.05 was considered significant.

RESULTS

All 15 studies met the inclusion criteria, as shown in Figure 1. Table 1 shows the characteristics of the detailed studies. It was shown that there were 15 randomized controlled studies with an overall of 850 learners: 745 were junior high school students and 105 were senior high school students. There were five studies conducted in the USA, four in the Philippines, three in Canada, and one in Japan, Singapore, and Thailand. A series of simulation-based activities were evaluated, including interactive computer-based interactions, 3D interactives, virtual realities, and other simulations. The control group ranged from conventional learning (PPT presentations, lectures, printed journals,and textbooks.) to other learning tools.

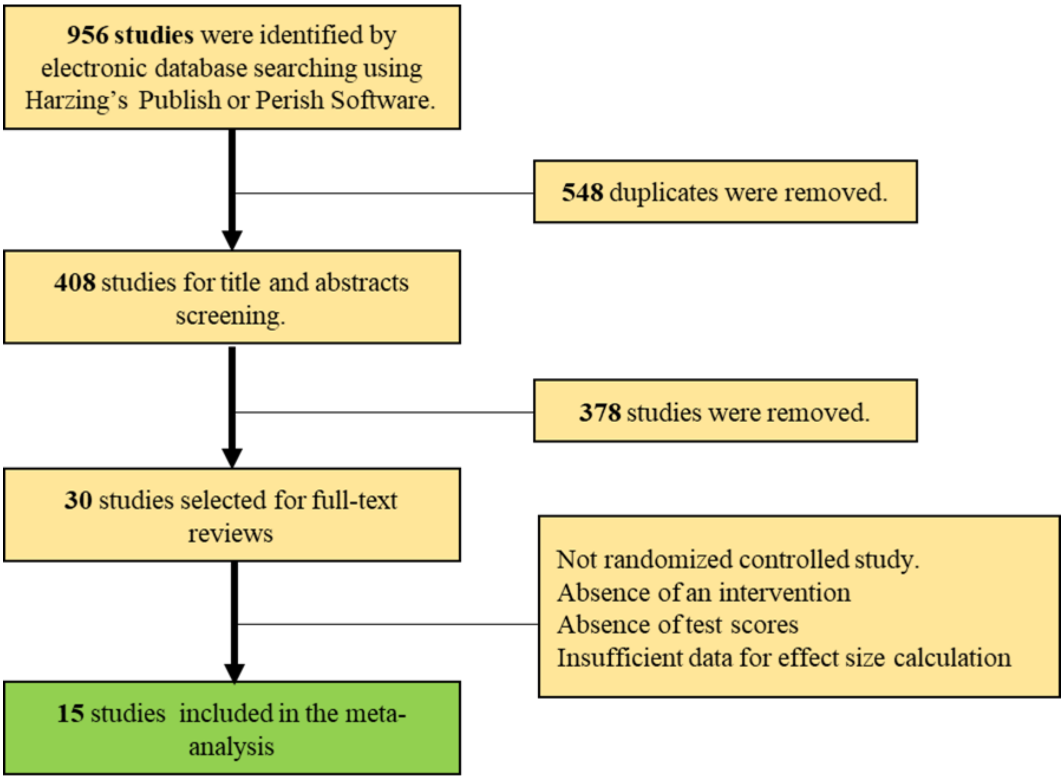

Fig. 1 Flowchart of the Search Strategy

Table 1 Characteristics of Involved Studies

First Author	N (SBA/Control)	Topic	Intervention	Comparator
Anthony, 2016	12/14	Anatomy	Virtual Reality	Dissection
Battulga, 2017	50/50	Cell Transport	3D Interactive	2D images
De Faria, 2016	28/28	Cell Division	3D Interactive	2D images
Ellington, 2018	16/15	Anatomy	Virtual Reality	PowerPoint
Hampton. 2016	21/22	Evolution	3D interactive	Immersions
Keedy, 2017	23/23	Cell Biology	3D Interactive	2D images
Knot, 2018	20/20	Cell Biology	Virtual Reality	Powerpoint
Kokoro, 2019	89/80	Cell Biology	3D Interactive	Powerpoint
Moro, 2017	20/22	Membrane	Virtual Reality	2D images
Nicholson, 2016	29/28	Anatomy	3D Interactive	Dissection
Seixas, 2017	15/15	Anatomy	3D Interactive	Textbooks
Solar, 2018	10/10	Cell Biology	Virtual Reality	Dissection
Stepan, 2017	33/33	Anatomy	Virtual Reality	Textbooks
Tan, 2016	21/21	Cell Biology	3D Interactive	Textbooks
Zachary, 2016	41/41	Anatomy	3D Interactive	2D images

Data analysis

The researcher classified the continuous test results from each study as primary and secondary outcome. The difference between groups in the outcome variables is associated with the development of the differing interventions. The primary outcome is the outcome of the highest importance. Scores on secondary outcomes are used to assess the additional effects of the intervention. In the detailed studies, all test scores are considered the primary outcome, and 5 out of 15 studies used satisfaction level as a secondary outcome. The forest plots of primary and secondary outcomes are presented in Figures 3 and 4. The effectiveness of simulation-based activities on tests scores was stated in all studies. The studies measured test scores as a primary outcome with standardized multiple-choice questionnaires. The researcher found that simulation-based activities significantly improvedlearners'test scores equated with conventional learning in the random-effects model. Figure 3 shows the SMD = 0.53 ($p < 0.05$, 95% CI 0.09–0.97) and I2 value of 87.8%.

Nine out of 5 studies showed that simulation-based activities significantly improvedstudents'test scores when compared with conventional learning (PPT presentations, lecture, printed journals,and textbooks) to other teaching tools; and five out of the 15 studies were not able to show statistically significant effects between the simulation-based activities and the control groups. Results showed that thedetailed studies were heterogeneous ($p < 0.001$), and it was also revealed that the actual effects were not consistent in all studies.

Five of the studies used satisfaction levels as a secondary outcome. The gathered results were based on the fixed-effects model. Most student-respondents are more interested in learning via simulation-based activities than conventional teaching methods. It has SMD value of 0.77 (95% CI 0.47–1.07, $p < 0.05$; I2 = 20.5%). However,only one study stated some antagonistic effects to some participants who used the simulation-based activities, including dizziness, eyestrain, headaches, or blurred vision.

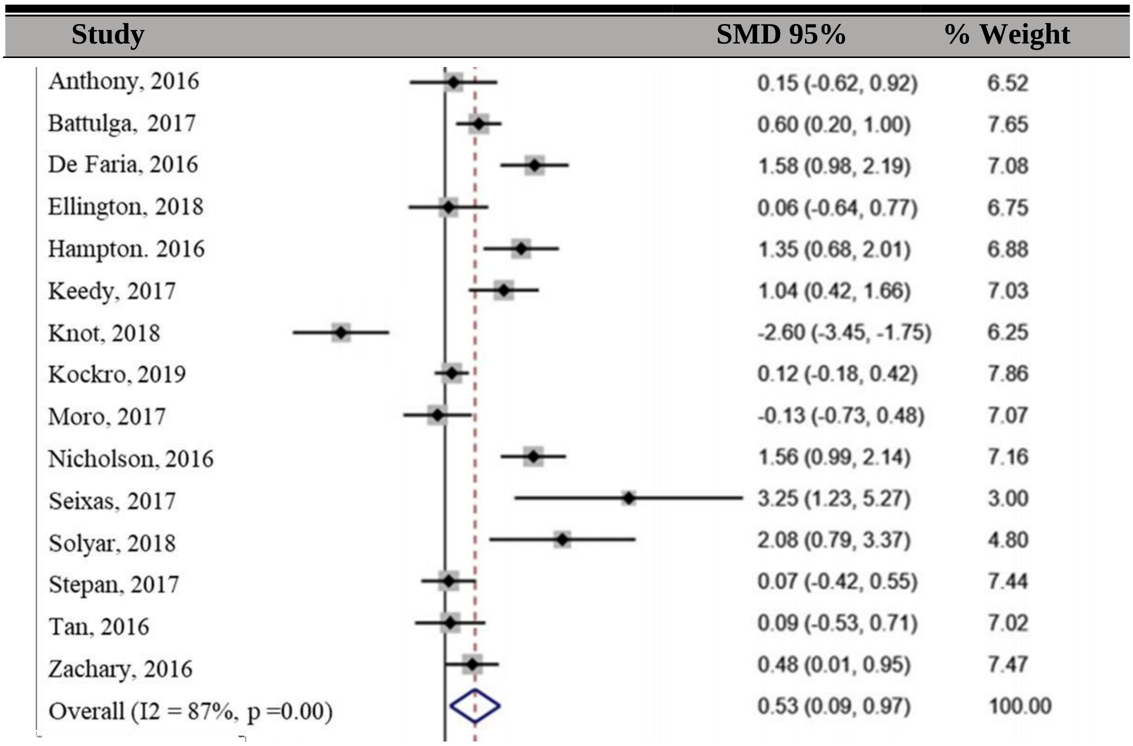

Fig. 2 Forest Plot for Test Scores

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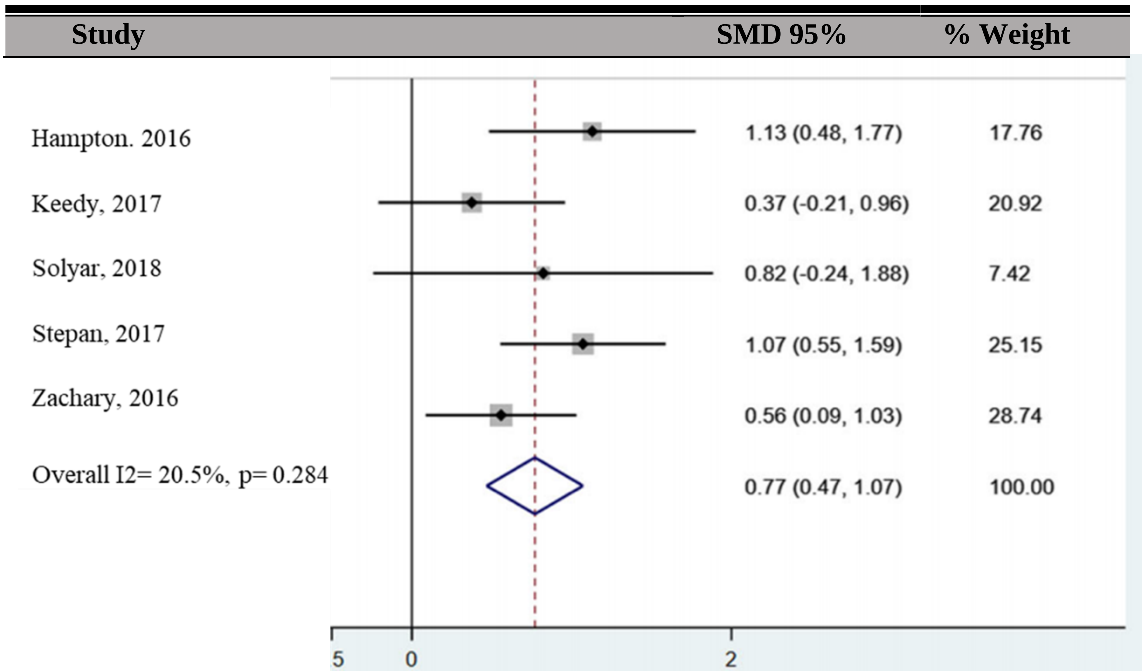

Fig. 3 Forest Plot for Satisfactory Level

Subgroup Analyses

Because of the heterogeneity of the subgroups, the researcher decided to usea random-effects model for the subgroup analysis,as shown in the results of the tests. As shown in Table 2, the categorical variables were as follows: topic (cell biology or anatomy or others), intervention (3D interactive models or Virtual reality simulations), and the comparator (conventional methods and other tools. Other possible moderators could not be examined because they were stated inadequately to do a subgroup analysis. The results have shown that the differences in the variables for Q statistics are non-significant (I2 > 75%).

Table 2 Summary Statistics for Moderators

Subgroup	N	SMD	95% CI	*p-value*	I^2
Topic					
▪ Cell Biology	8	-0.07	-0.95, 0.81	0.88	91.4%
▪ Anatomy	6	0.52	0.02, 1.01	0.04*	84.9%
▪ Others	1	0.34	0.52,2.14	0.68	87.8%
Intervention					
▪ 3D Interactive	9	0.64	0.00	0.00	82.5%
▪ Virtual Reality	6	-0.09	0.50	0.50	89.2%
Comparator					
▪ Conventional	7	0.78	0.15, 1.47	0.02*	82.6%
▪ Digital	8	0.34	-0.25, 0.95	0.25	90.2%

*statistically significant

Surprisingly, the moderator analysis revealed significant benefits for simulation-based activities in the subgroup of anatomy topics (SMD = 0.52; 95 percent confidence interval [CI] 0.02–1.01, p = 0.04), but no effect for SBAs in the subgroups of Cell biology and other topics (SMD = -0.07 and 0.34, respectively, p = 0.68). Additionally, moderator analysis of the control type revealed that the simulation-based activity group's test scores were not significantly better than those using other digital methods (SMD = 0.34; 95 percent confidence interval [CI] -0.25–0.95, p = 0.25), but were significantly better than those using conventional intervention methods (SMD = 0.78; 95 percent CI 0.15–1.47, p = 0.02).

Meta-regression analyses

The researcher conducted meta-regression analyses to identify any moderation effects on primary outcomes. The effect sizes on three potential moderators were regressed: course, intervention, and comparator. As revealed in Table 3, none of the moderators were significant at a level of $p < 0.05$.

Sensitivity analyses

Because of the remarkably high heterogeneity (> 75%), a sensitivity analysis was conducted to confirm the reliability of the results. When any study was removed from the model, the significant results of the simulation-based activities effect on test scores were unchanged in the models (SMD = 0.53, 95% CI: 0.01–1.07) as shown in Figure 4. Thus, the results revealed that the findings for test scores were reliable.

Table 3 Meta-regression Analysis for the Sources of Heterogeneity Factors

Factors	Coefficient	Std. Error	95% Cl	*p -value*
Topic	-0.26	0.89	−2.01, 1.49	0.77
Intervention	-0.33	0.79	−0.53, 0.27	0.67
Comparator	0.29	0.86	−1.40, 1.99	0.73

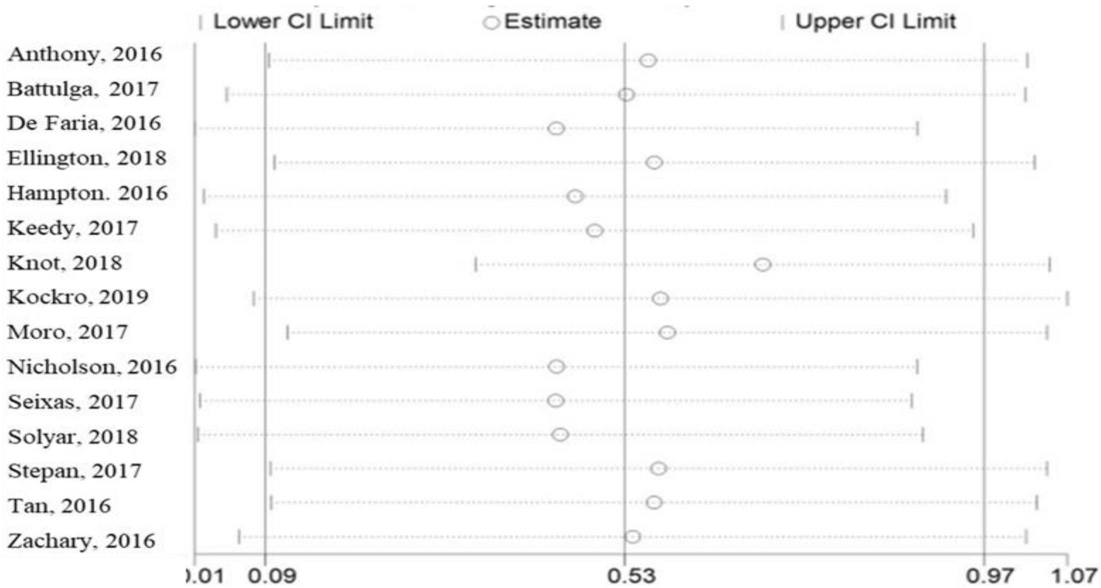

Fig. 4 Sensitivity analysis assessing the influence of each study

Discussion

This meta-analysis was employed to determine the effectiveness of simulation-based activities in teaching biology. The researcher found that SBA interventions have a moderate effectwith an SMD value of 0.53 in the students'test scores compared toconventional and digital methods ($p < 0.01$). This result coincides with Shiozawa's (2017) work, which stated that more interactive interventions could moderately enhance test scores in anatomy. Of all the 15 studies, five evaluatedthe satisfaction level as a secondary outcome,which shows that most students were more interested in using simulation-based activities to learn biology. Due to the lack of qualitative and descriptive data, the risk of bias for most studies wasuncertain. Theoretically,a high risk of partisan reporting bias was recognized in some research. The sensitivity and subgroup analyses were not significant for the subgroups - topic, intervention, and comparator. The researcher considered that because of inconsistent methodological methods in research in this meta-analysis,it is hard to formulate accurate conclusions.

In the subgroup analysis for learning topics, the basis of high heterogeneity could be the diversity of curriculum from each country and the level of difficulty of each case in Cell Biology and Anatomyin biology class. The high-level heterogeneity can also be attributed to the group of learners. First-year high school students are the participants in two studies (Nicholson, 2016 and Stepan, 2017), while the participants in the other two studies are fourth-yearsenior high school students(Hampton, 2016 & Keedy, 2016). High-level learners acquired more learning of biology. As stated in the study of Hattie et al. (2015), students' different levelsof knowledge and skills are remarkable in educational assessment. In addition, accessory organs, bodyparts, organelles, and other cellular processes are learned in different complexity levels, resulting in the heterogeneity of the gathereddata.This was supported by Stepan (2017), who stated that studyingthe parts and functions of the brain was confirmed harder thanlearning the skeletal system. The different type of comparators is another source of heterogeneity. Five from the 15 studies were included where these simulation-based activities were compared to conventional methods such as textbooks, lectures, and printed journals. For several decades, dissection has beenconsidered the standard teaching strategy for anatomyclasses.

Onlytwo studies compared simulation-based activities with dissection for teaching anatomy in this meta-analysis. In the study of Biasuttoet al. (2006),he stated that the best practice in teaching anatomy is the correct integration of dissections activities and computer-basedactivities. For the analysis of the satisfaction level, the results from the comparison of simulation-based activities versus others wereremarkably in favor of simulation-based activities. Most of the participants in the detailed studies revealed that the simulation-based activities were more user-friendly and more enjoyable to use. As supported by Bleakley (2014), he stated that there was a significant positive correlation between motivation and students' academic records.Nevertheless, because of the complex and comprehensive anatomical terms and concepts, 75% of participants found the simulation-based activities disorienting and frustrating (Moro, 2017). In addition, Rebenitsch (2016)explained that the use ofsimulation-based activities could result in cybersickness, such as eye strain, blurred vision, nausea, and headache. Therefore, more studies should focus on the adverse effects such as blurred vision and disorientation caused by simulation-based activities.

Limitations

This meta-analysis has several weaknesses and limitations. First, all the detailed studies mainly stated post-intervention results; therefore, the researcher could not analyze the pre-to post-interventionmodification. The researcher also considered that the validity of the different assessment tools and instruments used in the detailed studies might be biased. In the paper of Bleakley (2014), he emphasized that gender can also affect the learning performance of the students in medical schools. However, it was not easy to acquiregender information in the current systematic review. Another limitation was that none of the studies determined the cost and maintenance of the simulation-based intervention. For future research, other variables may also be collected for further analysis, such as region, duration of the intervention, gender ratio of the treatment, and control. Further research, conduct evaluations of studies that compare the different features of digital-based methods rather than those which compare digital-based to traditional methods.

Implications

As educational institutions adapt to the new normal of teaching remotely, one of the emerging educational technologies is simulation-based activities. It has the potentialto revolutionizebiology teaching. Thissystematic review showed that when compared with conventional ordigital teaching methods, simulation-based activities can enhance the effectiveness of teaching and learning biology. On the contrary, the researcher emphasized that themeta-analysis results are not suredue to the lack of standardized procedures and high heterogeneity of the studies and subgroups. Simulation-based activities as an intervention couldbe considered to enhance the quality ofteaching biology.

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