Effectiveness of Virtual Laboratories in Science Education: A Meta-Analysis

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***Abstract*—The development of technologies had transformed the way we deliver our instruction to the students. Many researchers and teachers alike are advocating for the integration of technology into their instruction as it provides promising results. One key aspect as to which technology can be of great help is through virtual laboratory activities. This meta-analysis offered information on the effectiveness of using virtual laboratory activities to student achievement. Results of the meta-analysis revealed a medium effect size (*g* = 0.587) towards the use of virtual laboratories. The subject area and level of study were used as subgrouping to further explore the effectiveness of conducting virtual laboratories.**

***Index Terms*—Educational technology, laboratory activities, meta-analysis, virtual laboratories.**

I. Introduction

Laboratory activities are an essential part of every science curriculum as they provide the practical applications of the theories studied by the students as well as opportunities to develop practical skills [1], [2]. Throughout time, it has been established that laboratory activities enhance students' understanding and attitude towards the different science courses [3], [4]. To provide more evidence, in the field of chemistry education, chemistry laboratory activities play a vital role in the development of the students' conceptual understanding of various chemical principles. and their attitude towards learning chemistry [5]. Although most studies have revealed that laboratory activities yield positive effects to the students, most schools in developing countries would not even have a viable laboratory mainly due to cost and maintenance [6]. Furthermore, some studies have reported hesitancy in implementing laboratory activities because of the potential risks to safety and time constraints [7]. Therefore, science educators continue to find innovative ways to deliver laboratory activities to students [4].

With the way technology has been shaping the educational landscape [8], [9], an innovative way to deliver laboratory activities with not the much-added cost is through virtual laboratories [10]–[12]. Virtual laboratories provide simulated versions of traditional laboratories where the learner is provided with virtual representations of the real objects used in traditional laboratories [9], [13], [14]. Toth *et al*. [15] mentioned that virtual laboratories allow the students to conduct the same scientific inquiry afforded by traditional laboratory activities but at a reduced cost [16], hazards [9], and time constraints. In contrast with traditional laboratory activities, virtual laboratory activities allow students to have unlimited opportunities to re-do the simulations that can aid in further conceptual development [17]. Virtual learning environments also offer instant feedback from data manipulations, as well as opportunities to practice and prepare for conceptually complex hands-on experiments [18].

Despite the positive reports in the implementation of virtual laboratory activities, certain criticisms of virtual laboratory activities were made (difficult to integrate into the learning process [19], [20]; lack of practicality [17]; negative student attitudes [20]). Furthermore, while most of the studies focused on the implementation of virtual laboratories to physics and chemistry education, little attention was given to other pertinent science education subject areas such as biology and earth science. Lastly, most of the available studies in virtual laboratory activities included pre-service teachers who are expected to have already possessed foundational concepts. Samples that included secondary and elementary students were somehow limited. Thus, this study aims to establish the effect of implementing virtual laboratory activities compared to a traditional laboratory on student academic achievement in science courses through a comprehensive meta-analysis.

To establish the effectiveness of virtual laboratory activities in improving student academic achievement in science education, the present study wishes to conduct a meta-analysis to determine the following:

1) The overall effect size of the use of virtual laboratories on student achievement in science discourses against traditional laboratory set-ups.
2) A statistically significant difference between virtual and traditional laboratory activities when subject area and level of study were used as sub-group.

II. Methods

A. Meta-Analysis

As defined by Glass [21], meta-analysis is the "statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings". The study is in a form of survey research where previously done work is surveyed instead of people [22]. Furthermore, doing meta-analysis allows the researcher to formulate reliable general statements since the process of doing such combines relative sample and effect size of previously done work [23]. Specifically, Glass *et al*. [24] prescribed steps to perform meta-analysis which includes 1) collection of studies, 2) coding features of the study, 3) calculation of the effect

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size in a particular construct, 4) investigation of the moderating effects of a study's characteristics on outcome measures.

B. Search Protocol

The studies included in this paper were searched mainly from Google Scholar, and Scopus since both databases when used in systematic reviews offered stability of coverage [25]. Since the Scopus database contains most of the articles found in other databases, it was used jointly with the ScienceDirect database for cases where full-text papers cannot be accessed through Scopus. Additionally, the Crossref database was used to look for additional research that includes published studies in conference proceedings. The key terms used in searching for the articles were "Virtual Laboratories", "Virtual Lab" coupled with "Science", "Science Education" and "Student Achievement".

C. Inclusion and Exclusion Criteria

To evaluate the effectiveness of using virtual laboratories in science education, meta-analysis was utilized on qualified studies. Titles and abstracts of the gathered studies were inspected for the following five criteria:

1) The study must explicitly made use of virtual laboratories as its intervention in a science discourse which includes, Biology, Chemistry, Earth Science, and Physics at either undergraduate or K-12 level.
2) The study measured student achievement in either of the scientific discourse previously mentioned.
3) The study employed either the use of quasi-experimental or experimental research designs; this was added in the inclusion criteria to ensure that studies made use of virtual laboratories as educational interventions and that the measure variable of learning gains be correspondent to the implementation of virtual laboratories and not of random chance.
4) The study provided the necessary statistical information to compute for the effect size (e.g., sample size, standard deviation, mean, t-values, Cohen's d).
5) The study is written in English and was published in a peer-reviewed journal or included in a conference proceeding within the years 2015–2020. The year 2015–2020 was chosen for this study since some literature reviews [26] were done already in 2000 until early 2010. Instead of adding to their work, the researchers decided to venture on newer studies that passed the criteria set for this meta-analysis.

Studies were excluded from the meta-analysis if the article 1) did not come from either a peer-reviewed journal article or at the least conference proceeding; 2) no control group was used (traditional laboratories), or 3) lack of statistical information which would not allow for the computation of effect size (hedge's g).

D. Identification and Selection of Studies for Inclusion

The first phase of identifying and selecting the studies for inclusion in the meta-analysis is through a database search. Google Scholar, Scopus, and Crossref databases were utilized using the key terms mentioned earlier. A total of 1172 studies were collected and were reviewed against the inclusion criteria through an inspection of the titles and abstract. 11 studies were excluded after inspection for duplication. A total of 63 studies remained after examination of which 970 were excluded due to the inappropriateness of key terms in the title while 128 studies were excluded after the review of the abstract.

The remaining 63 studies entered the second phase of identifying and selecting the studies which include a full paper review. 28 studies were excluded from the meta-analysis due to a lack of data for student achievement in science. Majority of the 28 studies measured attitude towards virtual laboratories which is an outcome not included in this study. Furthermore, 20 studies were excluded because of the lack of statistical information that would hinder the computation of the effect size. Although some papers reported the mean and sample sizes, the standard deviations were not presented which would not allow for the determination of the effect size. After the two phases of reviews, 15 studies were included to participate in the meta-analysis. Fig. 1 illustrates and summarized the whole identification and selection of studies done in this paper.

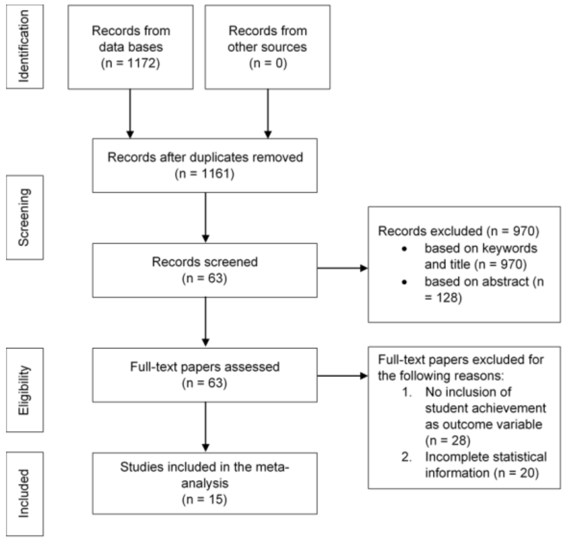

Fig. 1. Flow diagram of article selection.

E. Effect Size Calculation and Data Analysis

As described by Hedges & Olkin [27], the effect size and the standard error of the effect sizes were calculated using the software Comprehensive Meta-Analysis (CMA) of Borenstein *et al*. [28] to conduct a meta-analysis. Effect size in this study is reported using Hedge's g since Hedge's g is better than Cohen's d in adjusting for small sample size bias [29].

For this meta-analysis, the means and standard deviations were primarily selected to compute the effect size. Out of the 15 studies included in the analysis, only the study [30] utilized the means and t-test value to compute the effect size. As suggested by Lipsey & Wilson [22], a single effect size was calculated across all studies to prevent overall effect size bias due to statistical dependence which resulted from multiple effect size coming from one study. In studies that utilize unique research designs like multiple experimental and control groups, and experiments or assessments, the weighted average was used to determine single effect size. Moreover, for studies that included multiple constructs, careful determination of effect size basing on the selection criteria was used to determine the single effect size [31].

The random effects model was used to present the pooled effect size in this meta-analysis since according to Borenstein *et al*. [29] a random effects model is more appropriate for studies that differ in effect sizes and source of data. To support the use of the random effects model in reporting the pooled effect size and to confirm the subgroup analysis, a test for heterogeneity will be considered by calculating the Q statistic and the I^2 statistic. The null hypothesis of homogeneity is rejected when the Q statistic is significant. Furthermore, a significant Q statistic suggests that the variability between effect sizes is greater compared to the probable result of subject-level sampling error alone [22]. In the case of I^2 statistic, 25%, 50%, and 75% are associated to have low heterogeneity, moderate heterogeneity, and high heterogeneity respectively [28].

III. Results

Out of the 1172 papers initially retrieved from the literature search, a total of 15 studies that met the inclusion criteria previously mentioned in this paper were used for meta-analysis. Table I shows the summary of the studies depicting significant details. The total sample size is N = 2642 students where n = 1392 experience virtual laboratory experiments and n = 1250 students underwent traditional laboratory set-ups. The sample size per study ranges from 30-526 participants. Two studies made use of post-test only measurement while the majority of the studies utilized a quasi-experimental design (n = 8) Other studies made use of random experimental design (n = 6) and mixed-method (n = 1).

TABLE I: Summary of Included Studies for Meta-Analysis

Study (year)	Sample size	Virtual lab (Tradional lab)	Subject (level)	Method	Measurement
Ambusaidi *et al*. [32]	68	35 (33)	Chemistry (Secondary)	QED	Pre-test & Post-test
Chao *et al*. (2015) [33]	30	16 (14)	Chemistry (Secondary)	QED	Pre-test & Post-test
Faour & Ayoubi (2018) [13]	50	25 (25)	Physics (Secondary)	RED	Pre-test & Post-test
Ghergulescu *et al*. (2019) [34]	78	42 (36)	Chemistry (Secondary)	QED	Pre-test & Post-test
Herga *et al*. (2015) [35]	225	144 (81)	Chemistry (Secondary)	RED	Post-test only
Herga *et al*. (2016) [36]	109	62 (47)	Chemistry (Secondary)	RED	Post-test only
Hodges *et al*. (2018) [37]	351	184 (167)	Chemistry (Secondary)	MIX	Pre-test & Post-test
Husnaini & Chen (2019) [38]	68	34 (34)	Physics (Secondary)	RED	Pre-test & Post-test
Makransky etl al. (2016) [39]	189	95 (94)	Biology (Undergraduate)	RED	Pre-test & Post-test
Oser & Fraser (2015) [40]	322	169 (153)	Biology (Secondary)	QED	Post-test only
Ranjan (2017) [30]	208	105 (103)	Physics (Secondary)	QED	Pre-test & Post-test
Sapriadil *et al*, (2019) [41]	70	35 (35)	Physics (Secondary)	QED	Pre-test & Post-test
Sari Ay & Yilmaz (2015) [42]	69	36 (33)	Physics (Secondary)	QED	Pre-test & Post-test
Usman *et al*. (2019) [43]	526	269 (257)	Earth Science (Secondary)	QED	Pre-test & Post-test
Winkelmann *et al*. (2020) [44]	279	141 (138)	Chemistry (Secondary)	RED	Pre-test & Post-test

*RED = Random Experimental Design, QED = Quasi-Experimental Design, MIX = Mixed Research Design.

A. *Overall Effect Size of Virtual Laboratory Activities*

The forest plot of the overall effect size is presented in Fig. 2. As presented in Fig. 2, four studies [32], [38]–[40] resulted in negative effect size towards the implementation of virtual laboratory activities while the remaining 11 were positive towards virtual laboratory activities which range from an effect size of 0.050 to 1.938. Only one study [44] resulted in a positive effect size that is not significant at $p < 0.05$. The overall effect size using the random effects model resulted to a value of g = 0.587 (SE = 0.141; 95% confidence interval 0.310–0.865) is statistically significant. Furthermore, the overall effect size is interpreted to have a medium effect size [45], [46].

Testing for heterogeneity, the I^2 resulted in a value of 91.063% which can be interpreted to have high heterogeneity [47] implying that either a subgroup or moderator analysis be made. Therefore, the meta-analysis can proceed with the second objective of subgrouping analysis of the level of study and subject area.

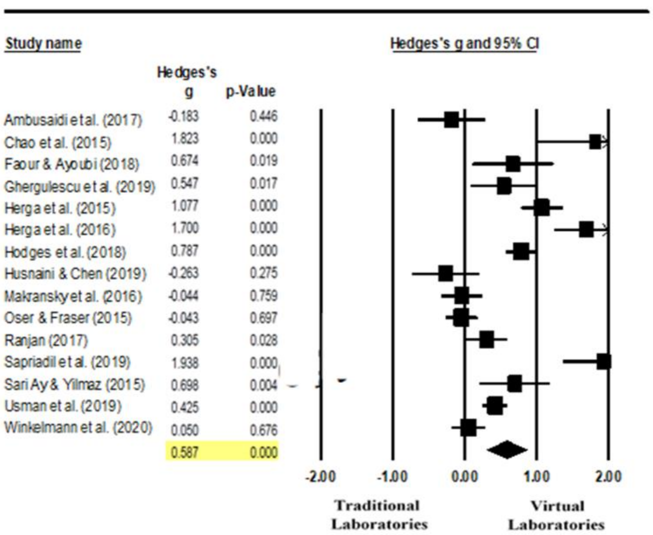

Fig. 2. Forest plot of effect sizes per study.

B. Subgroup Analysis

1) Level of study

Undergraduate students were observed to have a very small effect size (*g* = 0.012, *n* = 468) compared to secondary students' medium effect size (*g* = 0.689, *n* = 2174). The overall effect size when the level of study is used as subgrouping yielded to *g* = 0.186 which accounts for a small effect size [45], [46] showing statistical significance ($p < 0.025$, *SE* 0.079). The results of this subgroup analysis may indicate that virtual laboratory activities are effective when implemented to secondary students.

2) Subject area

The mixed effect analysis was used to perform further statistical analysis. The subject area of Biology (*g* = -0.044, *n* = 511) received a negative effect size while Chemistry (g = 0.787, *n* = 1140) Earth Science (*g* = 0.425, *n* = 526), and Physics (*g* = 0.652, *n* = 465) all resulted to a positive effect size. Chemistry received the highest effect size among all subject area. The overall effect size when grouped according to subject area is g = 0.244 which is analogous to a small effect size is statistically significant (*p < 0.025, SE* = 0.059*)*. All in all, the result of the subgroup analysis for the subject area yielded with a small effect size that is statistically significant may imply that across all subject areas in science, virtual laboratories could have improved student achievement with physics and chemistry having the most benefit.

C. Publication Bias

Although initial visual inspection of the funnel plot (see Fig. 3) suggests asymmetric distribution towards the bottom right side of the plot, both the rank correlation test (Kendal tau = 0.27 *p* = 0.07) and Egger's regression test (intercept = 2.92, *p* = 0.09) resulted in statistically insignificant coefficient suggesting that to accept the null hypothesis, there should be symmetric distribution. As suggested, a symmetric plot means the absence of publication bias in the meta-analysis [48], [49]. Furthermore, the Classic fail-safe N test revealed that there are 524 additional studies needed to nullify the overall effect size calculated in this study [50]. To further support the claim of the absence of publication bias, Orwin's fail-safe N was determined revealing that 637 missing studies are needed to bring the effect size to a trivial value (*g* = 0.01) [51].

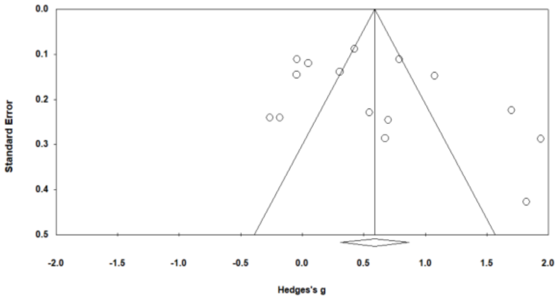

Fig. 3. Funnel plot.

IV. Discussion

As technology gets more accessible and sophisticated, integrating technology into educational environments is inevitable [52]. A clear integration of technology into the educational environment is through virtual laboratories. Virtual laboratories are simulations of the traditional hands-on experiment where virtual representations are used [13]. To establish the effect of virtual laboratories on science education, this meta-analysis explored studies that implemented virtual laboratory experiments against traditional laboratory set-ups. While there were meta-analysis studies about computer-simulated instruction [31], [53]–[55] and bibliographic review studies [20], [52], there were no meta-analyses (to the best knowledge of the researchers) done specifically to the application of virtual laboratories in science education. Furthermore, the subject area and level of study were considered as a subgroup to verify if virtual laboratory activities are effective on the subgroups identified.

A total of 15 studies were included and analyzed in this meta-analysis. All the studies made use of the virtual laboratory to science disciplines which include Biology, Chemistry, Earth Science, and Physics. A standardized Hedge's g was calculated for each study to prevent statistical bias [22]. The overall effect size using the random effects model resulted in a value of *g* = 0.587 (*SE* = 0.141; 95% confidence interval 0.310–0.865) is statistically significant and considered to have a medium effect size. The result of the meta-analysis is consistent with previous efforts to look at the overall effects of virtual simulations in educational environments. Merchant *et al*. [31] revealed that students who received instruction using desktop virtual simulations outperformed those using traditional set-ups. It could be noted that students performed well upon implementation of virtual laboratories since students doing traditional laboratory activities focus more on the practical and physical aspects rather than the variables being explored in the experiment [56]. Another factor that might have caused increased cognitive outcomes for students using virtual laboratories is their exposure time. Hands-on laboratories are only allowed for a limited time and are not ideal for repetition [57]; while virtual laboratories allow students to repeat the experiment with no added cost [38], [58]. In doing so, students have more opportunities to understand the underlying concepts being studied in their science class.

The level of study was as a subgrouping in this meta-analysis to verify if virtual laboratories work effectively in both secondary and undergraduate levels. The results revealed that when grouped according to the level of study using the mixed effect analysis the overall hedge's g value is 0.186 (*SE* = 0.079, *p* = 0.020) which is categorized to have small effect size. Secondary level students were observed to benefit most from virtual laboratories due to an observed medium effect size (*g* = 0.689, *n* = 2174) while undergraduate students received only a small effect size (*g* = 0.012, *n* = 468).

The subject area was also used as a subgroup to determine the effect of virtual laboratories on Chemistry, Physics, Biology, and Earth Science. Using the mixed effect analysis, the overall effect size was calculated to have a Hedge's g value of 0.244 (*SE* = 0.059, *p* = 0.000) and is interpreted to have a small effect size [11], [12]. The subject area of chemistry received the highest effect size (g = 0.787, n = 1140) while a negative effect size was observed for Biology (g = -0.044, n = 511). Arguably, the observed negative effect size in Biology is non-conclusive and may not have represented the entire literature due to the limitation that only two studies were included and analyzed. Oser & Fraser [40] suggested that even if virtual laboratories were not an effective strategy in making significant learning gains to the students, it could still be used as supplementary instruction that would not negatively affect the students. Virtual laboratories in the field of biology could still be a good way to prepare students before the actual laboratory since the use of virtual laboratories reduces the cognitive load of the students [59], [60].

V. Educational Implications

The decision to promote and use virtual laboratories is still at the judgment of the teachers and administrators since additional provisions for cost and teacher training shall follow when implemented. As revealed by the meta-analysis, there is a medium effect size indicating that the use of virtual laboratories can indeed promote a better understanding of scientific concepts.

Through this meta-analysis, the overall effect of virtual laboratories on student achievement has been calculated using a standardized Hedge's g. Furthermore, the effect of virtual laboratories on subgroupings such as level of study and subject area was reported. Because of this, students and administrators can have a basis to inform them on the implementation of a promising intervention that integrates technology.

Thus, the integration and use of virtual laboratories should be further explored by future researchers so that a more sophisticated way of delivery can be empirically explored. Teachers might consider coupling the use of virtual laboratories which is a good constructivist approach [61] to other well-known science education teaching principles to maximize further the learning gains of the students. A possible blending is through problem-based learning. Since science education offers practical and observable phenomena, the use of carefully designed projects and testing in virtual laboratories could possibly allow students to have a deeper understanding of the theories and concepts behind natural phenomena presented in the problems [62].

Another consideration in the use of virtual laboratories is the design and implementation of the activities. Estriegana *et al*. [19], suggested that efficiency and playfulness are factors that positively influence the student's adoption of e-learning systems since playfulness and enjoyment engage students towards the learning process thus motivating them to accept the use of these tools. Furthermore, it was considered that cognitive, affective, psychomotor skills influence each other even on virtual learning set-ups [63]; thus, implying that teachers and even developers to consider sophisticated designs to ease the use of virtual learning.

Lastly, the issue of collaboration must be able addressed as well by teachers. Possible ways were identified by Herdio *et al*. [52], which includes the integration to LMS which supports synchronous and asynchronous collaboration tools, the integration of virtual laboratory activities to virtual reality devices, and the development of technology that would support multiple users at a time.

A. Limitations of the Study

The inclusion and exclusion criteria discussed in this paper suggest that studies not published in peer-review journals and conferences were excluded from the meta-analysis. Although it might be argued that publishers often publish positive results [64], there were studies included in this meta-analysis that yielded negative effect sizes. In this case, the results of this paper are limited only to the studies included for meta-analysis and may possibly not be representative of the entire effect size. Furthermore, the study is limited only to student achievement measures and is not in itself explaining factors such as motivations and attitudes towards the use of virtual laboratory experiments in science education. The subgrouping explored in the study was also limited by the studies that had passed our inclusion criteria thus this paper acts as an initial attempt to guide instructors and designers on the possible effects of level of study and subject area on the implementation of virtual laboratories.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.L. Santos conducted the research, analyzed the data, and wrote the manuscript. M. Prudente supervised and give very insightful ideas throughout the conduct of the study.

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