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Teaching electric circuits using tangible and graphical user interfaces: A meta-analysis

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Abstract
Laboratories are considered to play a unique role in circuits teaching. Laboratories can be traditional, with physical components and desks, or virtual with graphical simulators. Applying these facilities in teaching, students can make experiments or measurements by exploring electric circuits' features. However, an intriguing research question is whether physical components or graphical simulators are more appropriate to build knowledge, enhance skills and improve attitudes. Thus, the aim of this article is: 1) to perform a review in order to explore the characteristics of the studies that compare the tangible and graphical user interfaces and 2) to apply a meta-analysis for the effects of the interfaces under study. The meta-analysis included 88 studies with pre/post-tests designs with 2798 participants, which were emerged from: a) 4 databases, b) forward snowballing method. The review showed that the majority of researchers have focused on the knowledge gaining, while a few researchers have examined skills and attitudes. The meta-analysis showed that the combination of user interfaces (tangible/graphical) appears to be the most beneficial for students in the domain of electric circuits teaching.

Keywords TUI · GUI · Electric circuits · Meta-analysis

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1 Introduction

Today, where the use of technology and its tools has penetrated formal and informal education, two ways of teaching laboratory courses can be identified: a) the traditional one with tangible user interface (TUI), which "*in general may be considered as physical objects whose manipulation may trigger various digital effects, providing ways for innovative play and learning*" (Sapounidis et al., 2016, p. 273), and b) the virtual one with graphical user interface (GUI), which through technology provides simulations (Maatuk et al., 2022; Sapounidis et al., 2019; Thees et al., 2022; Xie et al., 2020). Moreover, the use of simulations has also been established in courses where participation in labs with TUI is considered essential, such as science teaching and electric circuits (Pan et al., 2022; Salta et al., 2022). In real experimentation, it is assumed that the circuit might be connected to a computer or contain components like microcontrollers. Therefore, if the user presses a button, or even changes the position, values, and orientation of real circuits' components, this can directly affect the output of the circuit, so in this article the term tangible user interface (TUI) is adopted throughout.

Real laboratories in many cases, might contain tangible components along with measuring instruments, experimental setups, as well as expensive specialized equipment (Altmeyer et al., 2020; Finkelstein et al., 2005; Wörner et al., 2022). Their main advantage is direct physical contact with the activities to be studied (Akçayir et al., 2016). According to some researchers, physical contact might activate multiple senses and therefore can have a beneficial effect on a student's cognitive domain (e.g. Sapounidis et al., 2015). However, there are three main disadvantages of TUIs: a) it usually takes more time to prepare the activity/experiment, b) often, special equipment is needed and therefore is difficult to replace due to high cost in case of a damage, c) the results of real experimentation in some scientific fields are difficult to be observed (e.g. Evangelou & Kotsis, 2019; Olympiou & Zacharia, 2018; Zacharia & Olympiou, 2011). For example, the students will not be able to see the particles directly in a subatomic particle interaction experiment.

In contrast, GUI offers a safer and more immediate visualization of the phenomena, providing an infinite number of modifications and repetitions of the experiment at no cost, while the time for the implementation of the experiment is reduced in comparison to a real lab (Olympiou & Zacharia, 2012; Potkonjak et al., 2016; Puntambekar et al., 2021; Villena-Taranilla et al., 2022; Zacharia & Constantinou, 2008). Therefore, it is considered that virtual laboratories and simulations might overcome the disadvantages of real laboratories and tangible experimentation (Falloon, 2019; Tselegkaridis & Sapounidis, 2021). Yet, virtual labs may not offer a complete picture of the subject to a student. For instance, the consequences of wrong settings in the GUI are not easily perceived in contrast to the TUI, where one wrong setting can lead to the destruction of the equipment.

Undoubtedly, teaching through virtual labs and GUIs has been a common practice for years and was not created for the needs of the pandemic (Baran et al., 2020; Chernikova et al., 2020; Foronda et al., 2020; Reeves & Crippen, 2021;

Tselegkaridis & Sapounidis, 2022a). More specifically, during the pandemic period the use of this technology has been intensified (Xie et al., 2020). However, while societies are opting to return to new normality and students return to physical labs using tangible components, we do not know which of the conditions -GUIs or TUIs- or a combination of these two interfaces can be the most beneficial for students' learning (Kapp et al., 2020; Renken & Nunez, 2013; Sapounidis & Demetriadis, 2013; Sullivan et al., 2017). In detail, the relative studies appear to be quite limited presenting contradictory results. Therefore, the present article focuses on electric circuits and presents a meta-analysis, enlightening the characteristics of the studies along with the impact of the interfaces on students' knowledge, attitude, and skills (DerSimonian & Laird, 2015; Munn et al., 2018). As far as we know, this is the first meta-analysis that has been performed in this field. Thus, this article broadens the agenda in teaching electric circuits while at the same time is strengthening our understanding of the interfaces' impact.

The rest of the article is organized as follows: in Sect. 2 the theoretical background of previous research is given, while Sect. 3 focuses on the methodology of the review. In Sect. 4 the results are developed, in Sect. 5 there is a discussion of the findings, and finally, in Sect. 6 the conclusions are descripted.

2 Background

Researchers have looked into the factors that can contribute to students' performance in education (Lazonder & Harmsen, 2016). Consequently, some of them explored the level of guidance along with teachers' understanding of students' difficulties (Kapici et al., 2022). The results depict that if teachers understand their students' difficulties while learning, then they can support them more efficiently (Engelhardt & Beichner, 2004; Gaigher, 2014; Hmelo-Silver et al., 2007; Moodley & Gaigher, 2019). According to some other researchers (e.g. Alfieri et al., 2011; Bretz, 2019; Minner et al., 2010) teaching science through laboratories might have a positive effect on students as long as they do not participate passively but in the context of inquiry-based learning. As well, this way of learning seems to offer a positive impact on students' attitudes toward science (Chen et al., 2014; Hofstein & Lunetta, 2004).

Usually, researchers examine how laboratory activities affect learning objectives (Sapounidis et al., 2023; Wörner et al., 2022). Learning objectives can be classified into the following domains: attitudes, knowledge and skills (Baartman & De Bruijn, 2011). In this direction, Unlu and Dokme (2011b) investigated the attitudes of 66 middle school students about electric circuit, through a 3-week intervention. The sample was divided into three groups, TUI, GUI, and mixed. The findings showed that students' attitudes had a statistically higher score when they took part in activities either only with GUI, or with a mixed interface. Faour and Ayoubi (2018) research, conducted in a middle school with a sample size of 50 students, compared TUI and GUI in terms of participants' attitudes. The intervention lasted 10 weeks and the findings showed that there were no statistically significant differences in the results from the two different groups. Also, the research of Kapici et al. (2020), which was carried out in a middle school with a sample size of 143 students, investigated students' attitudes. The sample was divided into three groups, TUI, GUI and Mixed and the intervention lasted 6 weeks. The results showed that there were no statistically significant differences between the three groups.

The research implemented by Farrokhnia and Esmailpour (2010), was carried out with the participation of 100 university students, investigating the skill of constructing a real circuit. So, the researchers measured the time it took the students to build the circuit with real components. The results showed that students who participated with GUI acquired the same skills as students who participated with TUI, since they did not need more time to construct the real circuit. Moreover, Kapici et al. (2022) conducted a research with 116 middle school students, and compared participants' inquiry skills and level of guidance in TUI—GUI. The students took part in an intervention that lasted 4 weeks. Four groups were created, one group worked with TUI and low level of guidance, one group worked with TUI and high level of guidance, one group worked with GUI and low level of guidance, and one group worked with GUI and high level of guidance. Students participated in a pre/posttest that included 28 questions referring to observation, classification, designing experiments and forming hypotheses. The results showed that there were no statistically significant differences between the inquiry skills in the two interfaces and the level of guidance.

The research implemented by Tsihouridis et al. (2013), was carried out with the participation of 73 high school students, in order to investigate students' knowledge. The intervention lasted 11 h and two groups were created, TUI and GUI. The results showed that there was no statistically significant difference between the two groups in their knowledge. Furthermore, the research by Taramopoulos et al. (2012), which was carried out with the participation of 32 middle school students, depicted similar results. The intervention lasted 17 h and there were no statistically significant differences between the students of the two groups who worked with TUI and GUI respectively. Nevertheless, the research of Zacharia and Michael (2016) conducted in a primary school with a sample size of 55 students, compared TUI, GUI and Mixed in terms of participants' knowledge. The intervention lasted 3 weeks and the results showed that the mixed interface was more conducive to knowledge of the electric circuits concepts than the use of TUI or GUI alone.

What is more, the research by Tsihouridis et al. (2015) investigated the effect of sequence in the mixed interface on students' conceptual understanding. The intervention lasted 7 h and 66 students of middle school took part. According to its findings, the sequence that started from TUI and turned to GUI has had even a slightly better performance, compared to the one that started from GUI and turned to TUI. That reveals that there may be some indications that the sequence between the interfaces might plays an important role.

Additionally, Falloon (2020) examined the case where learning is transferred from simulation to activities with real components. 40 five-year-old children took part in simple circuit activities. The findings showed that the students transferred successfully their knowledge from one interface to another.

Last but not least, Zacharia and de Jong (2014) showed that when the taught subject is simple circuits there is no interface that is more favourable to the students. However, when the taught subject is more complex circuits, it seems that the GUI prevails over the TUI. This may be due to the fact that in the GUI it is easy to make modifications/changes, while in the TUI this process is more difficult.

In conclusion, in each learning domain, results appear conflicting, without indicating any interface as more efficient. Hence, there is no indication of whether any domain is enhanced more by a particular interface. Thus, the aim of this article is to investigate the following Research Questions (RQ):

- RQ1 what are the characteristics of the compared (TUI—GUI) studies in the teaching of electric circuits
- RQ2 what are the results of these studies through a meta-analysis

These two RQs will enrich the research in this field and provide useful information and directions to educators and researchers.

3 Methods

The review was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Statement (Page et al., 2021).

3.1 Eligibility criteria

To enhance the reliability of the study, we followed the same strategy with other meta-analyses where only peer-reviewed journal articles were included (e.g. Sapounidis et al., 2023; Tingir et al., 2017). Moreover, articles that contain quantitative comparisons between TUI and GUI teaching electric circuits, in English language were searched. There were no restrictions placed on the year of publication. Articles related to distance education or remote laboratories were not included as we needed to achieve a clearer picture between the TUI and GUI comparison. Moreover, exclusion criteria (EC) were used: a) EC1 Off-topic articles, b) EC2 Experimental study that did not involve electric circuits, c) EC3 Study with a non-experimental design, and d) EC4 Study that was not accessible for retrieval.

3.2 Information sources and search strategy

Two strategies were used to search for articles: a) database search with a key-phrase, and b) forward snowballing method, which is the searching within the citing papers (Kondaveeti et al., 2021; Mourão et al., 2020).

Four well-known databases were used: Web of Science, Scopus, ERIC, and IEEEXplore. The search was conducted in 3–22 December 2022, and had the Boolean logic “(real OR hands-on OR physical) AND (virtual) AND (experiment* OR environment*) AND (circuit)”, adapted to each database.

3.3 Selection, data collection, and risk of bias

Two reviewers worked independently, examining the records and applying the inclusion/exclusion criteria. They arrived at the same results for most articles. In cases where there was uncertainty about a particular article, the reviewers engaged in discussions, presented their arguments, and together made the final decision.

It was crucial for each included article to have quantitative data (pre/post-test), so that sufficient data could be collected to perform the meta-analysis. An article usually contained multiple data, as multiple pre/post-tests were often used.

As shown in Table 1, out of a total of 3247 results from the 4 databases, 14 met the criteria. But 4 were duplicates, so 10 articles emerged.

Two of the articles that emerged from the database search, were selected for the number of references they had, 522 in total. In detail, articles were sought from those who had cited Kapici et al. (2019) and Zacharia (2007) in their research. As shown in Table 2, from these 522 references, 19 new articles that met the criteria emerged. However, 13 were duplicates, so 6 articles included, bringing the total to 16 from which we extracted data.

The 16 included articles described a total of 88 pre/post-tests, and these were used to perform the meta-analysis. Finally, Fig. 1 shows the PRISMA flowchart.

Table 1 Database search

Database	Findings	Articles in English	Excluded				Included
			EC1	EC2	EC3	EC4	
Web of Science	654	409	392	4	6	0	7
Scopus	1495	480	474	2	1	0	3
ERIC	22	16	2	4	5	1	4
IEEEXplore	1076	283	280	3	0	0	0
	3247	*1188*	*1148*	*13*	*12*	*1*	*14*
						Duplicated	*4*
						Unique	***10***

Table 2 Citation search

Citation searching	References	EC1	Included
Kapici et al.(2019)	71	68	3
Zacharia (2007)	451	435	16
	522	*503*	*19*
		Duplicated	*13*
		Unique	***6***

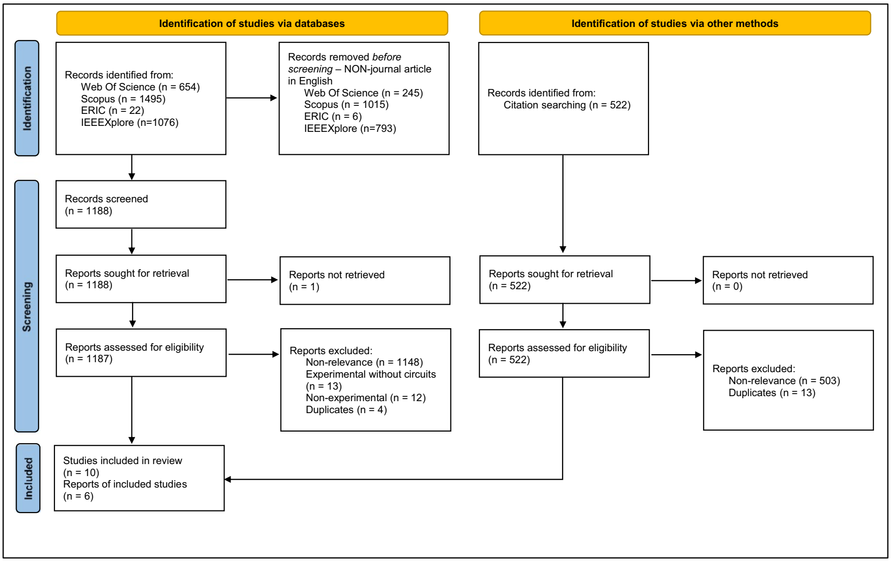

Fig. 1 PRISMA flowchart

4 Results

To be able to answer RQ1, we recorded data such as the sample size, the duration of the intervention, the school level, and the learning objective.

4.1 The features of the included studies

The findings (Table 3) show that approximately 44% of the articles were published in the period 2017–2022. The oldest article that emerged from the search is from 2005. Half of the articles were conducted in Asia, 31% in Europe, 12.5% in North America and 6.5% in Africa.

As shown in Fig. 2, 19% of the studies took place in a primary school, 38% in a middle school, 13% in a high school and 30% in a university.

12.5% of the investigations lasted up to 2 weeks, 50% up to 2 months and 37.5% up to a six-month period. About 38% of the studies had a sample size of up to 50 people, 31% up to 100 people, and 31% over 100 people. Only one study had a sample size of over 225 people. Figure 3 shows the sample size histogram.

Half of the articles (50%) compare TUI and GUI, while the other half (50%) compare TUI, GUI, and mixed interfaces.

The findings (Table 4) show that 75% of the articles set as learning objective the knowledge gaining, 15% the attitudes, and 10% the skills. Multiple choice questions were used as an evaluation tool in 38.5% of cases, open tests were used

Table 3 Features

ID	Article	Country	Continent	School Level	Sample size	Age	Duration	Comparison
1	Zacharia (2007)	Cyprus	Europe	University	90	20_22	Semester	TUI vs TUI_GUI
2	Kapici et al. (2022)	Turkey	Asia	Middle	116	12_14	4 h / 4 weeks	TUI vs GUI vs LevelOfGuidance
3	Kollöffel and de Jong (2013)	Netherlands	Europe	Secondary vocational	43	16_22	45 min / 9 weeks	TUI vs GUI
4	Zacharia and de Jong (2014)	Cyprus	Europe	University	194	20	90 min / 15 weeks	TUI vs GUI vs Mixed
5	Kapici et al. (2019)	Turkey	Asia	Middle	143	12_14	4 h / 4 weeks	TUI vs GUI vs Mixed
6	Kapici et al. (2020)	Turkey	Asia	Middle	143	12_13	6 weeks	TUI vs GUI vs Mixed
7	Manunure et al. (2020)	Zimbabwean	Africa	Middle	49	12_14	90 min / 3 weeks	TUI vs TUI_GUI
8	Jaakkola and Nurmi (2008)	Finland	Europe	Primary	66	10_11	2 weeks	TUI vs GUI vs Mixed
9	Jaakkola et al. (2011)	Finland	Europe	Primary	50	11_12	Week	GUI vs Mixed vs LevelOfGuidance
10	Finkelstein et al. (2005)	USA	North America	University	231	19_22	Semester	TUI vs GUI
11	Faour and Ayoubi (2018)	Lebanon	Asia	Middle	50	15	3*55/10 weeks	TUI vs GUI
12	Başer and Durmus (2010)	Turkey	Asia	University	80	19_22	4 h / 3 weeks	TUI vs GUI
13	Tekbıyık and Ercan (2015)	Turkey	Asia	Primary	65	10	5 weeks	TUI vs GUI
14	Unlu and Dokme (2011a)	Turkey	Asia	Middle	66	13	4 h / 3 weeks	TUI vs GUI vs Mixed
15	Amida et al. (2020)	USA	North America	University	14	22	Semester	TUI vs GUI vs LevelOfGuidance
16	Phanphech et al. (2019)	Thailand	Asia	High	40	14_16	4 weeks	TUI vs GUI

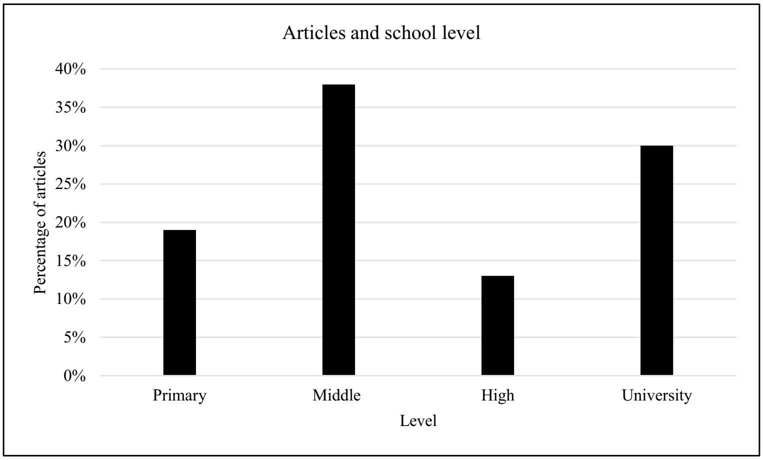

Fig. 2 School level

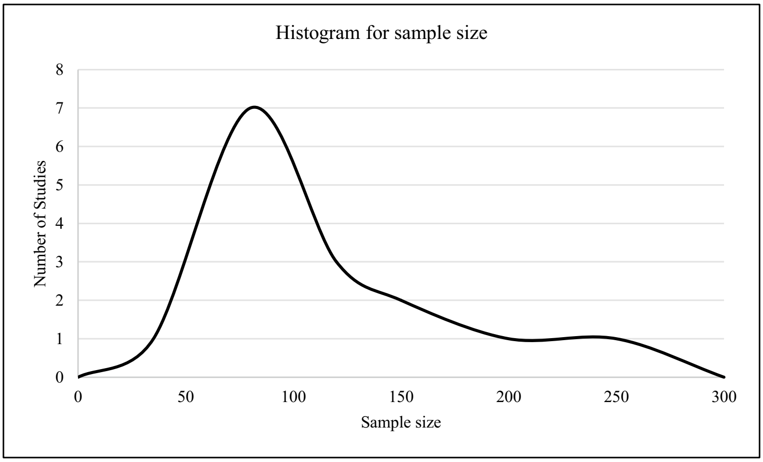

Fig. 3 Sample size

in 34.6%. Likert scale was used in 11.5% of cases, while true/false and matching questions were used in 7.7%.

4.2 Meta-analysis

4.2.1 Overall effect

From the 16 included articles, a total of 88 studies that implemented pre/post-tests designs were included in the meta-analysis, comprising a total number of 2798 students. The random-effects model was applied according to which the effect size is

Table 4 Results

ID	Evaluation tool					Learning Objective			Results
	True/False	*Multiple choice*	*Matching*	*Likert scale*	*Open test*	*Knowledge*	*Skill*	*Attitude*	
1		ν				ν			-Knowledge: Mixed interface is better than TUI
2	ν	ν	ν			ν	ν		-Knowledge: GUI is equal to TUI -Skills: GUI is equal to TUI -Level of guidance does not play any role on GUI vs TUI performance
3					ν	ν			-Knowledge: GUI is better than TUI
4					ν	ν			-Simple circuit: GUI is equal to TUI -Complex circuit: GUI is better than TUI
5	ν	ν	ν		ν	ν	ν		-Knowledge: Mixed interface is better than GUI -Skills: TUI is equal to GUI
6				ν				ν	-Attitude: Mixed interface is equal to TUI and GUI
7		ν				ν			-Knowledge: Mixed interface is better than TUI
8		ν			ν	ν			-Knowledge: Mixed interface is better than TUI and GUI
9		ν			ν	ν			-Level of guidance plays a role in GUI, but not in Mixed interface
10					ν	ν			-Knowledge: GUI is better than TUI
11		ν		ν		ν		ν	-Knowledge: GUI is better than TUI -Attitude: GUI is equal to TUI
12		ν				ν			-Knowledge: GUI is equal to TUI
13				ν	ν	ν		ν	-Knowledge: GUI is better than TUI -Attitude: GUI is equal to TUI
14		ν				ν			-Knowledge: Mixed interface is better than TUI and GUI
15					ν	ν			-Knowledge: GUI is equal to TUI -Level of guidance does not play any role on GUI vs TUI performance
16		ν			ν	ν			-Knowledge: GUI is better than TUI

considered a random variable (Borenstein et al., 2010; Rice et al., 2018), where it is expected that there is no one real effect, but a distribution of real effects. The Comprehensive Meta-Analysis (CMA) software was used to perform the calculations for the meta-analysis (Borenstein et al., 2022). Under the random-effects model, the summary estimate of the effect size (Hedge's g), of the use of laboratory environment on academic outcomes for electric circuits was + 1.669 with a 95% confidence interval of + 1.43 to + 1.907, with Z-value 13,713, $p < 0.001$. Eleven of the studies reported a negative effect size. In contrast, if using the fixed-effect model, the summary estimation of $r = 0.860$ with a 95% confidence interval has a lower limit of + 0.808 and an upper limit of + 0.913. Figure 4 shows the forest plot of random overall effect resulting from the meta-analysis.

4.2.2 Heterogeneity

Heterogeneity criterion was tested with Cochran's Q statistic. The null hypothesis states that there is a common true effect size for all studies. Cochran's Q statistic was $Q = 1733.915$, $df = 87$, $p < 0.01$, indicating inconsistent true results for several studies. The degree of heterogeneity is measured by the I^2 statistic, which was 94.982% indicating the percentage of the total variance that is due to the heterogeneity (Borenstein, 2020; Borenstein et al., 2017; IntHout et al., 2016). The value of $\tau^2 = 1.188$ and $\tau = 1.090$.

4.2.3 Publication bias

Publication bias was detected via the asymmetric funnel plots of standard error as shown in Fig. 5 that include only data from the empirical studies, while Fig. 6 includes data from both the present and imputed studies. Figure 7 shows the funnel plot of precision vs standard differences in means.

Egger's test confirmed the graphic inspection ($t[87] = 15.647$, $p < 0.01$). Rosenthal's fail-safe N = 1.889, suggests that about 1.889 studies should be added to the meta-analysis before the cumulative size effect would become statistically insignificant. The complete meta-analysis under the fixed-effect model showed a positive association of 0.860 between the use of laboratory environment and student academic outcomes. Duval and Tweedie's Trim and Fill method suggested that if we removed the asymmetric studies, this association would be reduced to 0.567.

4.2.4 Analysis of subgroups

The degree of heterogeneity (I^2 statistic) has shown that there are sources of variance in observed effect sizes different from the sampling error. This leads us to assume that some dimensions of subgroups might have different effect sizes and act as moderators. Thus, it is hypothesized that the use of laboratory activities for electric circuits have different effect sizes on the dependent variables:

- Learning Objective: *1) attitudes, 2) knowledge, 3) skills*
- School level: *1) primary, 2) middle or high school, 3) university*

ID	Effect Size	Std. Error	Lower	Upper	p-value	Weight
Başer & Durmuş. 2009	1.77	0.25	1.28	2.25	0.00	0.81
Başer & Durmuş. 2009	1.81	0.26	1.30	2.33	0.00	0.81
Jaakkola. Nurmi & Veer...	0.16	0.29	-0.41	0.73	0.58	0.80
Jaakkola. Nurmi & Veer...	0.78	0.31	0.18	1.38	0.01	0.79
Jaakkola. Nurmi & Veer...	1.51	0.42	0.68	2.34	0.00	0.74
Jaakkola. Nurmi & Veer...	1.25	0.38	0.49	2.00	0.00	0.76
Jaakkola & Nurmi. 2007	1.02	0.28	0.48	1.56	0.00	0.80
Jaakkola & Nurmi. 2007	0.66	0.24	0.20	1.12	0.01	0.82
Jaakkola & Nurmi. 2007	1.48	0.31	0.87	2.08	0.00	0.79
Kapici. Akcay & Cakir....	0.53	0.20	0.13	0.92	0.01	0.83
Kapici. Akcay & Cakir....	1.70	0.30	1.11	2.29	0.00	0.79
Kapici. Akcay & Cakir....	1.70	0.30	1.12	2.28	0.00	0.80
Kapici. Akcay & Cakir....	2.33	0.34	1.67	2.99	0.00	0.78
Kapici. Akcay & Cakir....	0.65	0.21	0.24	1.06	0.00	0.83
Kapici. Akcay & Cakir....	1.13	0.25	0.65	1.61	0.00	0.81
Kapici. Akcay & Cakir....	1.05	0.24	0.59	1.52	0.00	0.82
Kapici. Akcay & Cakir....	1.01	0.21	0.59	1.43	0.00	0.82
Kapici. Akcay & de Jon...	1.31	0.23	0.85	1.77	0.00	0.82
Kapici. Akcay & de Jon...	1.05	0.21	0.63	1.47	0.00	0.82
Kapici. Akcay & de Jon...	1.56	0.26	1.05	2.07	0.00	0.81
Kapici. Akcay & de Jon...	1.01	0.21	0.59	1.43	0.00	0.82
Kapici. Akcay & de Jon...	1.53	0.24	1.06	1.99	0.00	0.82
Kapici. Akcay & de Jon...	1.81	0.26	1.30	2.32	0.00	0.81
Kapici. Akcay & de Jon...	2.41	0.33	1.78	3.05	0.00	0.79
Kapici. Akcay & de Jon...	1.53	0.24	1.06	2.01	0.00	0.82
Kapici. Akcay & de Jon...	0.53	0.18	0.17	0.89	0.00	0.83
Kapici. Akcay & de Jon...	0.43	0.18	0.07	0.79	0.02	0.83
Kapici. Akcay & de Jon...	0.94	0.19	0.56	1.31	0.00	0.83
Kapici. Akcay & de Jon...	1.06	0.21	0.65	1.46	0.00	0.83
Kapici. Akcay & de Jon...	0.74	0.19	0.36	1.12	0.00	0.83
Kapici. Akcay & de Jon...	0.82	0.20	0.43	1.21	0.00	0.83
Kapici. Akcay & de Jon...	0.74	0.19	0.36	1.11	0.00	0.83
Kapici. Akcay & de Jon...	0.46	0.18	0.10	0.82	0.01	0.83
Kapici. Akcay & de Jon...	0.49	0.18	0.12	0.85	0.01	0.83
Kapici. Akcay & de Jon...	0.45	0.18	0.09	0.81	0.01	0.83
Kapici. Akcay & de Jon...	1.08	0.20	0.69	1.48	0.00	0.83
Kapici. Akcay & de Jon...	0.95	0.19	0.57	1.33	0.00	0.83
Kapici. Akcay & de Jon...	0.75	0.18	0.39	1.10	0.00	0.83
Kapici. Akcay & de Jon...	0.94	0.20	0.55	1.33	0.00	0.83
Kapici. Akcay & de Jon...	0.52	0.18	0.18	0.87	0.00	0.83
Kapici. Akcay & de Jon...	0.66	0.18	0.30	1.01	0.00	0.83
Kolloffel & de Jong. 2013	-0.21	0.23	-0.65	0.23	0.35	0.82
Kolloffel & de Jong. 2013	-0.54	0.24	-1.01	-0.07	0.02	0.82
Kolloffel & de Jong. 2013	-0.49	0.22	-0.92	-0.06	0.03	0.82
Kolloffel & de Jong. 2013	-1.48	0.30	-2.07	-0.89	0.00	0.79
Manunure. Delseriyes &...	1.61	0.30	1.01	2.20	0.00	0.79
Manunure. Delseriyes &...	2.37	0.39	1.60	3.13	0.00	0.76
Manunure. Delseriyes &...	1.51	0.29	0.94	2.08	0.00	0.80
Manunure. Delseriyes &...	2.26	0.38	1.52	3.00	0.00	0.76
Manunure. Delseriyes &...	1.22	0.27	0.69	1.75	0.00	0.81
Manunure. Delseriyes &...	1.42	0.29	0.86	1.99	0.00	0.80
Manunure. Delseriyes &...	1.11	0.26	0.61	1.62	0.00	0.81
Manunure. Delseriyes &...	1.69	0.32	1.07	2.31	0.00	0.79
Tekbiyik & Ercan. 2015	1.88	0.29	1.30	2.46	0.00	0.80
Tekbiyik & Ercan. 2015	1.58	0.26	1.06	2.09	0.00	0.81
Tekbiyik & Ercan. 2015	0.00	0.18	-0.35	0.35	1.00	0.83
Tekbiyik & Ercan. 2015	-0.29	0.18	-0.63	0.06	0.11	0.83
Tekbiyik & Ercan. 2015	0.00	0.18	-0.35	0.35	1.00	0.83
Tekbiyik & Ercan. 2015	-0.13	0.17	-0.47	0.21	0.46	0.83
Tekbiyik & Ercan. 2015	0.23	0.18	-0.13	0.58	0.21	0.83
Tekbiyik & Ercan. 2015	-0.42	0.18	-0.78	-0.06	0.02	0.83
Tekbiyik & Ercan. 2015	-0.18	0.18	-0.53	0.17	0.31	0.83
Tekbiyik & Ercan. 2015	-0.13	0.17	-0.47	0.21	0.46	0.83
Tekbiyik & Ercan. 2015	-0.11	0.18	-0.46	0.24	0.53	0.83
Tekbiyik & Ercan. 2015	-0.61	0.19	-0.98	-0.24	0.00	0.83
Ünlü & Dökme. 2011	1.78	0.35	1.09	2.46	0.00	0.77
Ünlü & Dökme. 2011	1.38	0.33	0.73	2.02	0.00	0.78
Ünlü & Dökme. 2011	3.35	0.49	2.38	4.32	0.00	0.71
Zacharia & de Jong. 2014	4.70	0.56	3.60	5.80	0.00	0.67
Zacharia & de Jong. 2014	5.26	0.63	4.04	6.49	0.00	0.64
Zacharia & de Jong. 2014	5.81	0.69	4.46	7.15	0.00	0.61
Zacharia & de Jong. 2014	5.58	0.66	4.29	6.87	0.00	0.62
Zacharia & de Jong. 2014	4.38	0.53	3.35	5.42	0.00	0.69
Zacharia & de Jong. 2014	3.85	0.47	2.93	4.78	0.00	0.72
Zacharia & de Jong. 2014	4.82	0.58	3.69	5.94	0.00	0.67
Zacharia & de Jong. 2014	4.38	0.53	3.35	5.42	0.00	0.69
Zacharia & de Jong. 2014	4.73	0.55	3.65	5.81	0.00	0.68
Zacharia & de Jong. 2014	3.68	0.44	2.81	4.54	0.00	0.73
Zacharia & de Jong. 2014	4.64	0.54	3.58	5.71	0.00	0.68
Zacharia & de Jong. 2014	4.23	0.50	3.25	5.21	0.00	0.71
Zacharia & de Jong. 2014	4.37	0.52	3.35	5.39	0.00	0.70
Zacharia & de Jong. 2014	4.71	0.56	3.62	5.80	0.00	0.68
Zacharia & de Jong. 2014	5.01	0.59	3.86	6.17	0.00	0.66
Zacharia & de Jong. 2014	4.94	0.58	3.80	6.07	0.00	0.66
Zacharia & de Jong. 2014	4.52	0.54	3.47	5.57	0.00	0.69
Zacharia & de Jong. 2014	4.79	0.57	3.68	5.90	0.00	0.67
Zacharia & de Jong. 2014	6.29	0.73	4.86	7.73	0.00	0.59
Zacharia & de Jong. 2014	5.68	0.66	4.38	6.98	0.00	0.62
Overall	1.67	0.12	1.43	1.90	0.00	

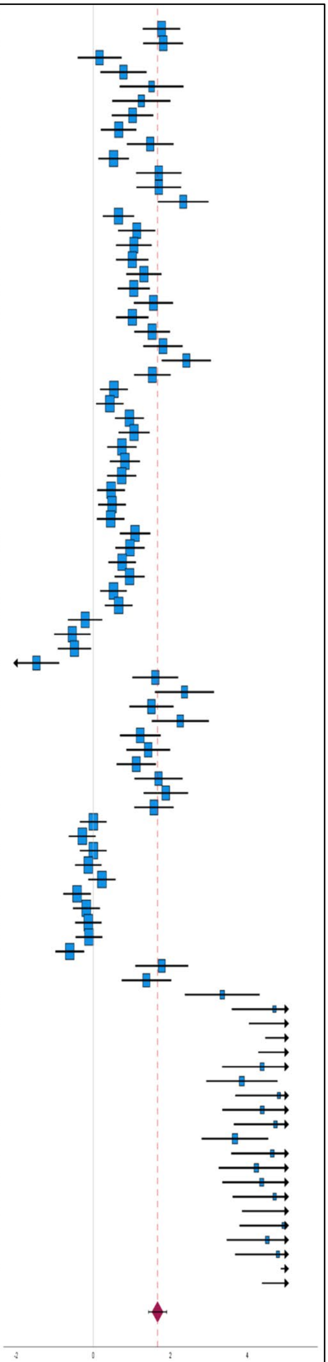

Fig. 4 Forest plot of random effect

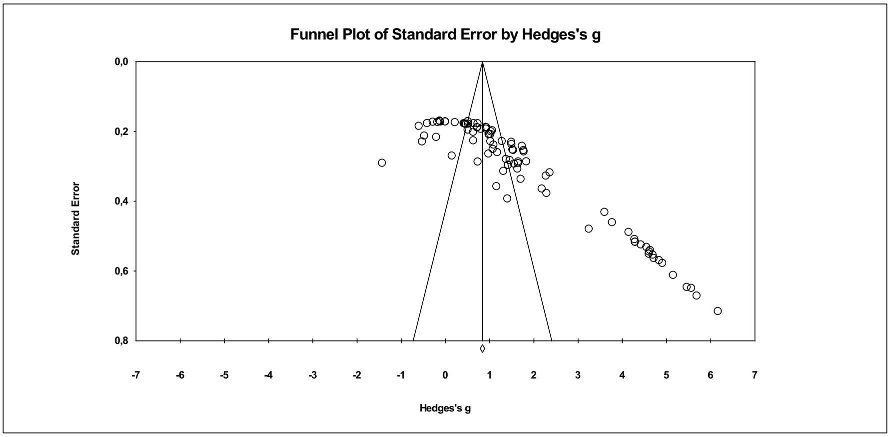

Fig. 5 Funnel plot with observed studies only

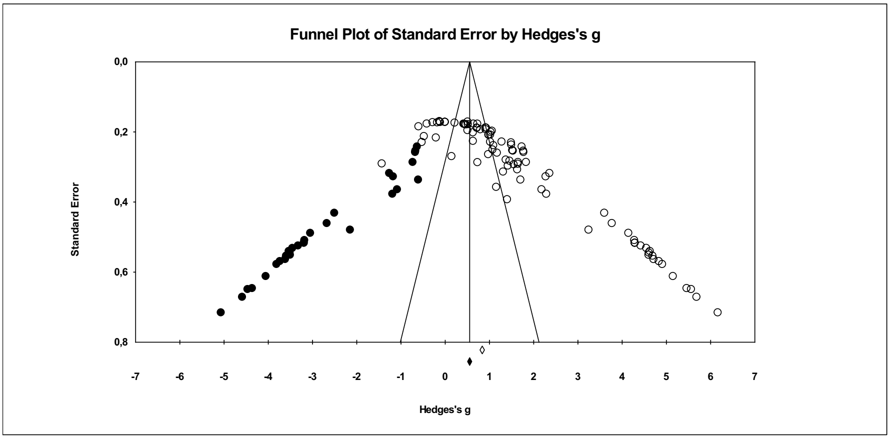

Fig. 6 Funnel plot with observed and imputed studies

- User Interface: *1) TUI, 2) GUI, 3) Mixed*

4.2.5 Analysis for learning objective

As shown in Table 5, fixed effect analysis showed that the I^2 statistic for attitudes, knowledge, and skills is 85.859%, 94.826%, and 44.984% respectively. Consequently, the random-effect model seems appropriate which provided the values of 0.316 for attitudes, 2.318 for knowledge, and 0.848 for skills. The effects are statistically significant at $p < 0.001$.

The comparison between effects of attitudes and knowledge gives $Q = 61.114$, $p < 0.05$. This shows that the effect sizes between attitudes and knowledge are statistically significant. Also, a comparison between the effects of knowledge and

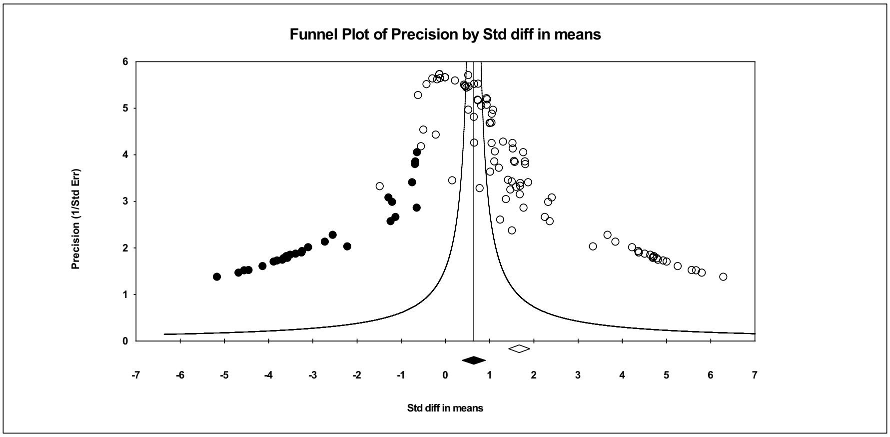

Fig. 7 Funnel plot of precision vs standard differences in means

skills gives Q = 10.893, $p < 0.05$, indicating that the difference of effect size between knowledge and skills are statistically significant. A comparison between the effects of attitudes and skills gives Q = 7.848, $p < 0.05$, that is the difference of effect size between skills and attitudes are statistically significant. Therefore, knowledge acquisition is the most beneficial from the use of laboratory for electric circuits.

4.2.6 Analysis for school level

As shown in Table 6, fixed effect analysis showed that the I^2 statistic for primary school, middle or high school, and university is 89.073%, 87.840%, and 89.271% respectively. Consequently, the random-effect model seems appropriate which provided the values of 0.415 for primary, 1.046 for middle or high school, and 4.377 for university. The effects are statistically significant at $p < 0.01$.

The comparison between effects of primary and middle or high school gives Q = 12.416, $p < 0.05$. This shows that the difference of effect size between primary and middle or high school are statistically significant. Also, a comparison between the effects of primary school and university gives Q = 131.247, $p < 0.05$, indicating that the difference of effect size between primary school and university are also statistically significant, as well. A comparison between the effects of middle or high school and university gives Q = 104.817, $p < 0.05$, that is the difference of effect size between middle or high school and university are also statistically significant. Therefore, students from university gained more benefits from the use of laboratory for electric circuits.

4.2.7 Analysis of user interface

As shown in Table 7, fixed effect analysis showed that the I^2 statistic for TUI, GUI, and Mixed is 94.918%, 93.618%, and 94.263% respectively. Consequently, the random-effect model seems appropriate which provided the values of 1.144 for

Table 5 Results of the separate meta-analysis for the learning objective

Fixed effect analysis								
	Studies	Estimated effect size	Standard error	Z-value	Q-value	df(Q)	*p*-value	I- squared
Attitudes	22	0.289	0.039	7.391**	148.499	21	0.000	85.859
Knowledge	58	1.535	0.042	36.540**	1101.572	57	0.000	94.826
Skills	8	0.810	0.072	11.169**	12.724	7	0.079	44.984
Random effect analysis								
	Studies	Estimated effect size	Standard error	Z-value				
Attitudes	22	0.316	0.204	1.550**				
Knowledge	58	2.318	0.134	17.343**				
Skills	8	0.848	0.339	2.498**				

** $p < 0.001$

Table 6 Results of the separate meta-analysis for the school level

Fixed effect analysis								
	Studies	Estimated effect size	Standard error	Z-value	Q-value	df(Q)	*p*-value	I- squared
Primary	19	0.153	0.049	3.120**	164.730	18	0.000	89.073
Middle or High	47	0.885	0.033	26.505**	378.277	46	0.000	87.840
University	22	3.738	0.103	36.419**	195.726	21	0.000	89.271
Random effect analysis								
	Studies	Estimated effect size	Standard error	Z-value				
Primary	19	0.415	0.169	2.452**				
Middle or High	47	1.046	0.108	9.697**				
University	22	4.377	0.187	23.354**				

** $p < 0.01$

Table 7 Results of the separate meta-analysis for user interface

Fixed effect analysis								
	Studies	Estimated effect size	Standard error	Z-value	Q-value	df(Q)	*p*-value	I- squared
TUI	29	0.599	0.044	13.700**	551.012	28	0.000	94.918
GUI	27	0.624	0.045	13.982**	407.389	26	0.000	93.618
Mixed	32	1.529	0.051	29.923**	540.348	31	0.000	94.263
Random effect analysis								
	Studies	Estimated effect size	Standard error	Z-value				
TUI	29	1.144	0.197	5.796**				
GUI	27	1.171	0.181	6.453**				
Mixed	32	2.585	0.221	11.677**				

** $p < 0.001$

TUI, 1.171 for GUI, and 2.585 for Mixed. The effects are statistically significant at $p < 0.001$.

The comparison between effects of TUI and GUI gives $Q = 0.010$, $p > 0.05$. This shows that the difference of effect size between TUI and GUI are not statistically significant. A comparison between the effects of GUI and Mixed gives $Q = 24.408$, $p < 0.05$, indicating that the difference of effect size between GUI and Mixed are statistically significant. Similarly, a comparison between the effects of TUI and Mixed gives $Q = 23.603$, $p < 0.05$, that is the difference of effect size between TUI and Mixed are also statistically significant. Therefore, the important finding is that the mixed user interface is the most beneficial from the use of laboratory for electric circuits.

5 Discussion

Regarding the features of the emerged articles, almost half of them were published in the period 2017–2022. This possibly indicates a growth in the field of designing educational interventions in electric circuits with different interfaces. If we consider that during the Coronavirus Disease 2019 (COVID-19) pandemic period, many educational activities were carried out virtually, then in the near future comparative (TUI-GUI) studies would be carried out and published.

About thirty percent of the research studies were conducted at a university. Our results also showed that several studies on teaching electric circuits were conducted in Turkey, while few were conducted in the United States. Nevertheless, in a similar field related to science, technology, engineering, and mathematics (STEM) education, the United States takes a leading role (Tselegkaridis & Sapounidis, 2022b). This disparity might be attributed to the differences between the fields and could possibly reflect the efforts made by Turkish researchers to develop this specific area. However, the included articles may not provide the overall picture of the field, or some studies may have been omitted. This may be due to the way the search was conducted, that is, from the specific words/keywords we used.

According to our findings, there were no participants younger than 10 years old. This aligns with the findings of Wörner et al. (2022), who demonstrated that no experiments are conducted in science education with children younger than third grade. A possible explanation for this may be that the subject of electric circuits is not extensively taught in early childhood. Based on Brenneman et al. (2019) early childhood teachers rarely receive adequate preparation to implement STEM activities. Additionally, according to Lu et al. (2022) and Ültay and Aktaş (2020) STEM education and research mostly focus on secondary and high school education.

Moreover, an important issue for any educational research is the duration of the intervention. About thirty-eight percent of the studies lasted a semester, while about ten percent lasted up to 2 weeks. Another equally important issue for safe inference is the sample size. About thirty-eight percent of the studies used up to 50 students, a small number considering that the intervention includes at least 2 groups of students for TUI and GUI. Consequently, statistical analysis of these sample sizes imposes some limitations.

About thirty percent of the studies used open-ended questions. In general, this is a factor that might contribute to the reliability and quality of the findings, as long as a rubric is used to grade the test. Nevertheless, the included articles did not mention the use of a rubric. Also, in forty percent of the studies, multiple-choice questions were used as an assessment tool.

According to the findings of Table 3, half of the articles compared the TUI with the GUI. In the domain of knowledge, some studies conclude that the GUI has a better learning effect than the TUI (e.g.Faour & Ayoubi, 2018; Kollöffel & de Jong, 2013; Tekbıyık & Ercan, 2015). However, other studies found no difference between TUI and GUI (e.g.Amida et al., 2020; Kapici et al., 2022). We notice that no study has reached a general conclusion that TUI is better than GUI. This finding may be attributed to the types of the exercises conducted during the interventions (Mathur & VanderWeele, 2020; Nakagawa et al., 2022). The other half of the articles compared mixed interfaces. In the domain of knowledge, the findings showed that mixed interfaces probably have a better learning result than TUI or GUI alone (e.g.Kapici et al., 2019; Manunure et al., 2020; Unlu & Dokme, 2011a; Zacharia, 2007).

From the above it can be concluded that the GUI leads to the same or better results than the TUI. Nevertheless, this feature should be investigated in several circuits with different activities. Moreover, students who engage in activities in a tangible and graphical way seem to benefit more in the domain of knowledge (Alkhaldi et al., 2016; de Jong et al., 2013; Wang & Tseng, 2018).

Regarding skills, the interface seems to play no role as no differences were observed between TUI and GUI (e.g. Kapici et al., 2022). Also, the findings showed that students' attitudes are not affected by the laboratory interface, since either in a TUI, GUI, or mixed interface, the results showed no differences (e.g. Faour & Ayoubi, 2018). However, as the number of the emerged articles was small, further development of such research is needed in order to enrich the field and draw more secure conclusions. As well, it should be noted that although all the studies had electric circuits as their subject, they did not have the same activities or common pre/post-tests designs.

The meta-analysis of the 88 studies with pre/post-tests designs, despite the fact of lacking homogeneity and detection of publication bias, has provided strong indications for the significant effects of laboratory activities on learning outcomes. Specifically, under the random-effects model, the summary estimate of the effect size was + 1.669 with a 95% confidence interval of + 1.43 to + 1.907, with Z-value 13,713, $p < 0.001$. This finding is consistent with other meta-analyses on the use of technology in education (e.g. Sapounidis et al., 2023; Schmid et al., 2014; Tingir et al., 2017). Knowledge appears to benefit significantly regarding skills and attitudes, while older students seem to benefit the most. As far as the effect of interfaces is concerned, it was shown that a mixed model achieves better results compared to activities involved merely TUI, or GUI. The meta-analysis supports the same findings as in the preceding review.

6 Conclusions

This article aims to shed light on aspects of the utilization of user interfaces in teaching electric circuits, through a meta-analysis. To achieve this, we searched and selected 16 articles that described experimental interventions and provide quantitative comparisons between TUI and GUI. Our findings show that out of the 16 emerged articles, nearly half of them have been published in the last 6 years. Moreover, 6 of the emerged articles had a sample size of up to 50 students, while in another 6 articles, the intervention lasted up to one semester. In addition, the majority of researchers compared interfaces and focused on knowledge building, while few researchers have studied students' skills and attitudes. After all, strengthening students' attitudes towards science issues may not have a direct impact on students' achievement, but it may affect positively their later engagement in those sciences.

In addition, a meta-analysis was conducted using 88 pre/post-tests. Despite the limitations, the findings demonstrated that the use of laboratory activities had a positive impact on students' learning outcomes, regardless of the interface. Specifically, the meta-analysis revealed the following results: a) the mixed use of interfaces yielded the best outcomes, b) older students achieved better results, and c) knowledge showed the most significant improvement compared to attitudes and skills. However, the literature needs to be enriched with more studies so that safer conclusions can be drawn.

Future work and recommendations Initially, it is very important in future work to frame the level of guidance in a very clear and specific way. If this is done in a systematic way, it will strengthen the findings and expand the research in this field. In addition, research should go beyond simple electric circuits and extend to the whole range of electric circuits. Furthermore, researchers should focus on studies of students' skills and attitudes, as our grasp of this aspect seems to be very limited. Finally, it is important for the researchers to pay attention to the sample size and the duration of the intervention, so that there will be depth and quality in their findings.

Author contributions All authors contributed to the study conception and design. All authors read and approved the final manuscript.

Data availability Data will be made available upon reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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