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How do Head-mounted Displays and Planning Strategy Influence Problem-solving-based Learning in Introductory Electrical Circuit Design?

Bian Wu[1*], Yiling Hu[1] and Minhong Wang[1,2]
[1]Department of Education Information Technology, East China Normal University, Shanghai, China // [2]KM&EL Lab, Faculty of Education, The University of Hong Kong, Hong Kong, China // bwu@deit.ecnu.edu.cn // ylhu@deit.ecnu.edu.cn // magwang@hku.hk
[*]Corresponding author

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ABSTRACT: The high-fidelity and interactivity afforded by head-mounted displays (HMD) has a potential to improve learning in problem-solving contexts. However, there is a lack of studies with mixed findings on the efficacy of HMD in the development of problem-solving competence. Moreover, the integration of learning strategies with HMD supported learning is often overlooked. This study aimed to address the gap by investigating whether the simulation media (HMD or 2D simulation environments) and learning strategy (with or without planning) may influence student learning with problem-solving tasks. The results show that the HMD and planning groups outperformed other groups in simulated problem-solving tasks, and in transferring the competence to real-world tasks. Students using the HMD perceived a higher level of sense of presence, self-efficacy, and simulator acceptance; but they reported a higher level of mental workload and simulator sickness than those using the 2D simulation. Implications of the findings are also discussed.

Keywords: Virtual reality, Simulations, Learning strategies, Problem solving

1. Introduction

Research on virtual reality in education has proliferated over the past decade. More recently, the head-mounted display (HMD) technology that provides personal perspectives in virtual reality settings offers a sense of immersion during learning, and is therefore being called immersive virtual reality (IVR). By adding immersive and interactive alternatives to traditional classroom settings, HMD environments may facilitate experiential learning, conceptual and procedural understanding, and psychomotor skill development (Concannon, Esmail, & Roberts, 2019). In particular, HDM may benefit learning in problem-solving contexts, which is material-saturated and requires body engagement (Chen, Hong, Sung, & Chang, 2011; Johri & Olds, 2011). HMD technology can enhance problem-solving-based learning by inducing more epistemic actions, i.e., actions that augment human cognition and help reveal hidden information (Jin & Lee, 2019).

Previous studies found that HMD environments of high-fidelity improve users' sense of presence, emotion, motivation, and technology acceptance (Chang, Heo, Yeh, Han, & Li, 2018; Cooper, Park, Nasr, Thong, & Johnson, 2019; Kwon, 2019; Makransky, Borre-Gude, & Mayer, 2019; Makransky & Lilleholt, 2018; Shu, Huang, Chang, & Chen, 2019; Zhang et al., 2020). Nevertheless, research also shows that HMD may increase learners' mental workload and sickness symptoms (Jost, Cobb, & Hämmerle, 2019; Meyer, Omdahl, & Makransky, 2019). It remains unclear if these findings of personal factors can be generalized to different HMD-based learning contexts, because the requirements of immersiveness and mental workload as well as affordances of HMD regarding visualization and interactivity may vary for different learning goals and in different VR-based learning applications (Wu, Yu, & Gu, 2020). In addition to self-reported learning experience, a few studies explored the effects of HMD on improving learning outcomes and found promising results regarding learning efficiency, skill acquisition and conceptual understanding (Huang, Luo, Yang, Lu, & Chen, 2020; Jung & Ahn, 2018; Parmar et al., 2016). While HMDs have a potential to foster experiential and problem-solving-based learning, there are, however, inadequate studies investigating the effects of HMD on problem-solving competence and the use of hands-on activities for performance-based assessment (Lamb, Antonenko, Etopio, & Seccia, 2018). In addition, existing studies on the effect of HMD on learning performance have not considered how well the competence was transferred from the simulated environment to real situations (Yang et al., 2018; Falloon, 2020).

Compared to computer-based 2D simulations or desktop VR, HMDs provide a high level of fidelity. However, prior research that compared HMDs and desktop simulations regarding their effects on problem-solving-based learning reported mixed results (Makransky, Terkildsen, & Mayer, 2019; Parmar et al., 2016). To optimize VR-supported simulation learning, Fowler (2015) and Meyer et al. (2019) suggested that VR as an innovative media should be integrated with theoretically sound pedagogical design. For example, Parong and Mayer (2018) found that students who summarized the lesson after each HMD segment performed significantly better on the post-test of conceptual understanding than the groups that did not, and Meyer et al. (2019) found that pre-training and HMD had an interaction effect on learning. Unterrainer and Owen (2006) indicated that participants who made a full mental plan before movements performed better in solving problems than those who immediately began task-related movements. Thinking aloud at the beginning of the process can stimulate conceptual knowledge understanding, which helps to improve the ability to devise a plan to solve the problems (Kani & Shahrill, 2015). Therefore, it is of interest to investigate whether a planning strategy can improve students' problem-solving performance in HMD environments.

Specifically, as learning electrical circuit design is concerned, previous studies (Zacharia, 2007; Chen et al., 2011; Jaakkola, Nurmi, & Veermans, 2011) revealed the benefits of combining simulation-based learning with real experimentation. However, although desktop simulation software is widely used in science and engineering education, it seems a challenge to transfer knowledge from 2D-based virtual environment to real practice (Richard & Taylor, 2015). Therefore, the study extends the line of inquiry to explore the effectiveness of HMD-based simulation context in support of problem-solving learning in electrical circuit design, which in turn, can contribute to our understanding regarding whether and how HMD can better complement the traditional approaches of lecturing and real lab experiment.

In sum, existing studies have reported positive evidence of the utility of HMD technology in educational settings. However, these studies have placed more attention to learner perceptions than learning outcomes. While a few studies explored the effects of HMD on improving knowledge retention and skill acquisition, and the effect of HMD on problem-solving performance remains unclear, let alone the effects of HMD on the transfer of learning beyond the simulation settings. Therefore, this study aimed to investigate whether HMD and planning strategies would influence student learning with problem-solving tasks in introductory electrical circuit design. The following three research questions were addressed.

RQ1: Will the simulation media (i.e., HMD or 2D simulation environments) and the learning strategy (i.e., with or without planning) influence students' problem-solving performance in simulated environments of electrical circuit design?

RQ2: Will the simulation media (i.e., HMD or 2D simulation environments) and the learning strategy (i.e., with or without planning) influence students' transfer of problem-solving competence from simulated tasks to real-world tasks in electrical circuit design?

RQ3: Will the simulation media (i.e., HMD or 2D simulation environments) and the learning strategy (i.e., with or without planning) influence students' perceptions of the problem-solving-based learning experience in electrical circuit design?

The perceptions include the participants' self-efficacy, sense of presence, simulator acceptance, perceived mental workload, and perceived simulator sickness, and their opinions on the use of HMD in problem-solving-based learning.

2. Method

2.1. Context and participants

Fifty-two first- and second-year undergraduate students (21 males, 31 females, mean age = 18.4 years, SD = 0.75 years) participated in this study voluntarily. They were teacher-students enrolled in an educational technology program at a university in eastern China. They participated in this study for the learning of electrical circuit design, as part of the professional development for pre-service STEM teachers. The exclusion criterion was the enrolled participants had taken any introductory electrical circuit design course at university level before this study. The study employed a two-factor experimental design: simulation media (HMD or 2D simulation environments) and learning strategy (with or without planning). The participants were randomly assigned to four conditions, with thirteen students in each condition. This research was approved by the ethical review board of the researchers' institution. All participants signed informed consent forms for their participation in this study.

Electrical-circuit design involves complex skills. Although real lab experiments or using simulators seems to be norm in teaching circuit design, there are many factors influence its adoption in China, such as higher education instructors' lack of student-centered teaching competence, knowledge-based and exam-oriented curriculum planning, and limited time for practice teaching (Wu, Liu, & Yi, 2012). The dominant pedagogy of this learning subject remains "chalk and talk," which limits students' practical experience (Mills & Treagust, 2003). In this study, students were asked to learn by using various electrical elements and devices to develop artifacts (i.e., electrical circuits) that meet the given requirements and constraints. In a simulation environment, if the electrical elements were connected correctly, the circuits would function as expected.

2.2. Learning environments and materials

For the HMD condition, we used Short Circuit VR, which is a free electrical VR simulator developed by Bauwens and Ho (2018). The simulation was displayed through HTC VIVE with a 110° horizontal field of view, a resolution of 2160 × 1200 pixels, 90 fps, 6-degree-of-freedom, handheld controllers and on HP Alienware (CPU i7-9700K 3.6 GHz, RAM 16.0 GB, GPU NVIDIA GTX1660Ti). For the desktop 2D-simulation condition, we used Breadboard Simulator v1.0, which is open-source software developed by Shah (2018). The two simulation environments for circuit design are shown in Figure 1.

We provided two circuit-design problems for the simulated learning experiment, which were conducted on either a 2D simulation on a PC or on an HMD-based simulation environment. The first problem required students to design a circuit to light up an LED. The students needed to understand the working principle of diode, the polarity of the LED, apply Ohm's law to choose the correct resistance, and make sure the current flowing through the LED was within the safe range. The second problem required students to control a seven-segment display such that the number "1" could be turned on and off using a push button. To complete this circuit design, the students needed to understand the mechanism and usage of some basic electrical components. The second problem was more difficult than the first one. The problems were developed by an instructor of introductory electrical circuit design course to make sure the experimental materials were comparable to the tasks that are normally given in the course.

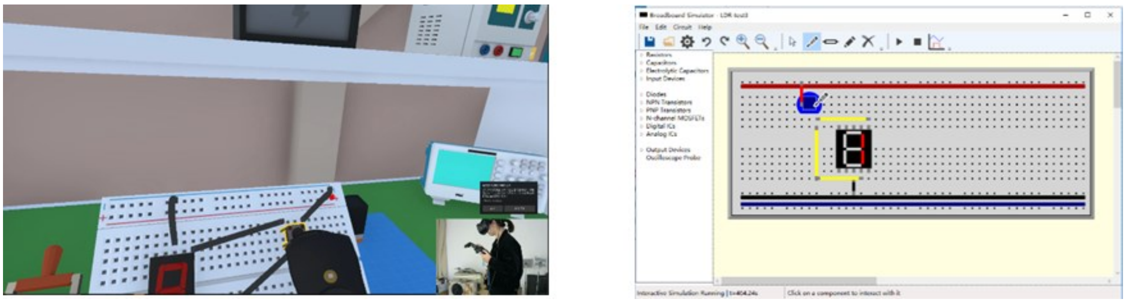

Figure 1. Screenshots from the simulation environments for electrical circuit design: The HMD condition using a Short Circuit VR environment (left) and the 2D simulation condition using a Breadboard Simulator environment (right)

2.3. Instruments

The pre-test questionnaire collected the participants' demographic information including their gender, age and whether they have taken any introductory electrical circuit design courses at university level or not. The post-test questionnaire consisted of measures of sense of presence, self-efficacy, mental workload, simulator sickness, and simulator acceptance (see Appendix 1 for the complete questionnaire). The sense of presence scale (four items) was adapted from Witmer and Singer (1998). The self-efficacy of learning scale (three items) was adapted from Meluso, Zheng, Spires, and Lester (2012). The mental workload scale (four items) was adapted from Hart and Staveland (1988). The simulator acceptance scale (five items) was adapted from Davis (1989) and Venkatesh and Bala (2008). The simulator sickness scale (three items) was adapted from Kennedy, Lane, Berbaum, and Lilienthal (1993). Cronbach's α was used to evaluate the internal consistency of each dimension. The Cronbach's α values was 0.8 for simulator acceptance, 0.81 for sense of presence, 0.72 for self-efficacy, 0.9 for mental workload and 0.58 for simulator sickness. With the exception of the value for simulator sickness, all these values were above the generally accepted cut-off for a satisfactory level of reliability (> 0.7) (Nunnally, 1978). The low reliability for simulator sickness was related to the participants' relative discomfort, such as their experience of dizziness, fatigue, or blurred vision. In addition to these scales, the 26 participants in the two HMD groups were asked two open-ended questions about whether they preferred learning problem-solving via HMD or via conventional learning methods (i.e., lecturing plus lab-based practice), and the pros and cons of using HMD to support problem-solving-based learning.

Problem-solving performance was measured in terms of success rate and completion time. A dichotomous variable was used as success rate. This variable was given a value of one if the participants solved the problem independently and successfully. If participants asked for help to solve a problem or failed to solve a problem, the variable was given a value of zero. The participants were informed that their time on task was measured as a proxy for performance. They were given five minutes for warming up and being familiar with their corresponding simulation environments before beginning the problem-solving tasks. The completion time was recorded in minutes.

Transfer of learning can be categorized into near transfer and far transfer (Nokes-Malach & Richey, 2015). The former is called for when students encounter problems that are very similar to the problems they have worked on during the learning phase. The latter is called for when students encounter problems that are new to them in both content and context. To assess the extent to which problem-solving competence was transferred from simulations to real-world tasks, the study included a post-transfer test comprising two further electrical circuit design problems that used a physical breadboard and real electrical components. The first, near-transfer problem asked the participants to control a seven-segment display so that number “1” turned on and off, but using a photoresistor instead of the push button used in the second learning task. This near-transfer problem is very similar to the training problem 2. The second, far-transfer problem was more complex than the two training problems and required the students to use a photoresistor to control a seven-segment display that switched between displaying the number “1” and the number “7.” Figure 2 shows the description of the second transfer problem and the real breadboard circuit design.

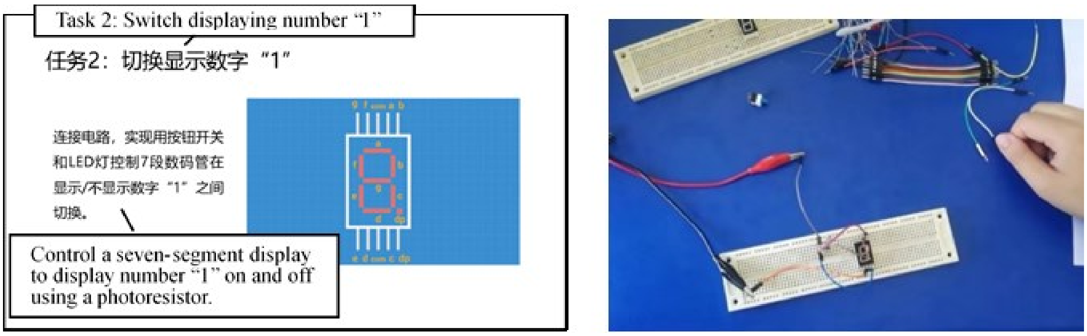

Figure 2. Description of the second transfer problem (left) and the real breadboard-based electrical circuit design (right)

2.4. Procedures

The participants registered the time slot for the experiment and attended the experiment one at a time in the VR-based learning laboratory with the help of one experimenter. The participants first read and signed a consent form. Then, they completed a pre-test questionnaire survey that collected their demographic information. The experimenter provided slides to illustrate the prerequisite concepts for understanding electrical circuits. All participants received the same slides about domain knowledge that are necessary for solving the following problems and learned at their own pace. They could also ask for explanation about the contents of these slides from the experimenter during individual learning. Then, the participants were shown another few slides demonstrated either the desktop 2D simulation environment or HMD and were given adequate time for familiarizing themselves with the assigned simulation environments. The total time for experiment preparation was around 20 minutes.

After warming up in simulation environment to reduce novel effect, the participants were given 60 minutes for the whole experiment of completing the two problems. The four groups were given slides tailored to the four different experimental conditions to describe the first problem with or without the planning requirement. The planning strategy asked the participants to think aloud, with the help of drawings, when planning their electrical-circuit design solutions, before performing the tasks in the simulation environments. They were informed about the time when they reached 30 minutes, but would not be interrupted even if they didn’t finish the first problem. When they thought they had completed the first problem, they could move on to read slides describing the second problem and tried to solve it in the same condition as the first one. When they reached 60 minutes, they would be stopped for the experiment no matter they have completed the two problems or not. The experimenter observed and recorded participants' performance in terms of completion time and problem-solving outcome. Webcam and screen capture software were also used to record both participants' gesture and body movement in the real world and their problem-solving process within the simulation environment. The recorded video data was used to verify the observation record.

After completing the experiments, the participants were required to solve two authentic transfer problems. Finally, they completed the post-test questionnaire survey. The post-simulation transfer test and questionnaire survey didn't have a time limit, but all the participants completed around 30 minutes. The research procedures are shown in Figure 3.

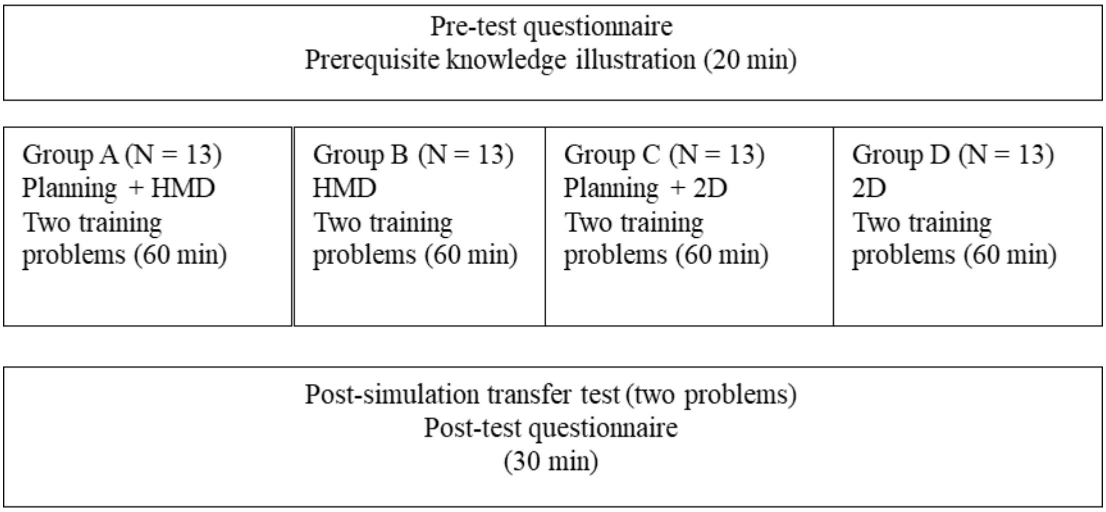

Figure 3. Procedure

2.5. Data analysis methods

To answer the first and the second research questions, we used the statistics of the problem-solving completion time and problem-solving success frequency in the four conditions. A two-way analysis of variance (ANOVA) was performed on the different problem-solving completion times to investigate the variance associated with the different media and the planning strategy. In addition, omega squared (ω^2) was used as an effect-size measure (Howell, 2006). Loglinear analysis was conducted on problem-solving success, media intervention, and planning intervention to examine the association between these three variables. We began with the saturated model, and removed the higher-order interactions first to identify the significant interaction effect. Then, to interpret the interaction, a chi-square test was performed and the odds ratio (*OR*) was calculated as a measure of the effect size.

To answer the third research question, we used descriptive statistics and a two-way ANOVA of sense of presence, self-efficacy, simulator sickness, and simulator acceptance. RStudio v1.2 (RStudio, 2019) and R v.3.6.1 (R Core Team, 2019) were used to run the quantitative analyses. The qualitative data collected through the open-ended questions were evaluated using a thematic analysis approach to triangulate the quantitative findings (Miles & Huberman, 1994). The responses were grouped into themes that reflected respondents' experiences of problem-solving-based learning through HMD. The themes were then ranked in order of frequency, to measure the relative importance of each theme. For each viewpoint, sample responses are presented in the results section.

3. Results

3.1. Problem-solving efficiency

Table 1 shows that the more difficult problem required more time to complete in both the training session and transfer test. Further, the results revealed that the HMD groups completed all four problems faster than did the 2D simulation groups. Moreover, the planning groups completed most of the problems faster than the groups without planning. It is intriguing to see that the group of 2D simulation without planning had a larger variation (SD = 11.76) in completion time of solving the second training problem. This might be due to the second training problem is relatively more difficult than the first one. Another noteworthy finding was the 2D simulation groups almost doubled the completion time in solving two transfer problems compared with the group of HMD with planning. A possible reason is the participants of 2D groups needed more time for processing information related with knowledge transfer into real context.

The two-way ANOVA revealed that the completion time of Problem 1 was the same for all four groups, with no significant main effects of media and method intervention or of the interaction effect. There was a significant main effect of method intervention, $F(1,48) = 5.97$, $p = .018$, $\omega^2 = 0.09$, on the completion time of Problem 2, but no significant main effect of media intervention or interaction effect. The completion time of the near-transfer problem had significant main effects from both media intervention, $F(1, 48) = 6.80$, $p = .012$, $\omega^2 = 0.09$ and method intervention, $F(1, 48) = 4.18$, $p = .046$, $\omega^2 = 0.05$, but no interaction effect. The completion time of the far-transfer problem had a significant main effect from media intervention, $F(1,48) = 5.51$, $p = .023$, $\omega^2 = 0.08$, but not from method intervention or interaction effect. According to Field, Miles, and Field (2013), a ω^2 less than 0.06 indicates a small effect size, between 0.06 and 0.14 is a medium effect size, and greater 0.14 is large effect size. Therefore, all the significant main effects for problem-solving efficiency had small-to-medium effect sizes.

Table 1. Means and standard deviations for problem-solving completion time (in minutes)

	Media						
	HMD		2D simulation		Media	Method	Interaction
	With planning	Without planning	With planning	Without planning	*p* value	*p* value	*p* value
Training problem 1	7.88 (5.37)	7.69 (4.55)	8.80 (6.82)	9.61 (5.92)	.375	.847	.754
Training problem 2	14.23 (8.33)	19.62 (7.87)	14.86 (9.18)	22.23 (11.76)	.536	.018*	.705
Near transfer problem	4.77 (1.74)	8.77 (4.30)	9.38 (5.39)	9.85 (3.36)	.012*	.046*	.112
Far transfer problem	5.69 (3.38)	8.38 (4.87)	10.38 (6.44)	11.08 (7.22)	.023*	.287	.527

Note. $^*p < .05$.

3.2. Problem-solving performance

Table 2 reports the success/failure frequencies of problem solving for the four problems in the four conditions, and the results of the chi-square test of the association between media or method and performance. The HMD with planning group and the 2D simulation without planning group had the best and worst performance, respectively, in all four problems. The HMD groups had more successes than the 2D simulation groups in all four problems, and the planning groups outperformed the non-planning groups in all problems except the first training problem.

Table 2. Success/Fail frequency of problem solving

	Media				Media x performance	Method x performance
	HMD		2D simulation			
	With planning	Without planning	With planning	Without planning	*p* value	*p* value
Training Problem 1	11/2	10/3	7/6	6/7	.020*	.560
Training Problem 2	8/5	3/10	3/10	3/10	.139	.139
Near-transfer problem	13/0	7/6	8/5	3/10	.011*	.002**
Far-transfer problem	11/2	9/4	8/5	6/7	.080	.244

Note. $^*p < .05$; $^{**}p < .01$.

The three-way loglinear analysis using backward elimination produced a final model that retained only one two-way interaction effect, which was the type of media and Problem 1 success, $\chi^2(1) = 5.44$, $p = .020$. Thus, based on the *OR*, the odds of Problem 1 success were 4.08 (1.06, 18.26) times higher for students trained with HMD than for students trained with 2D simulations. In the transfer test, there was a significant association between the type of media and whether the near-transfer problem was successfully solved ($\chi^2(1) = 6.47$, $p = .011$), and between adopting a planning strategy and successfully solving the near-transfer problem ($\chi^2(1) = 9.67$, $p = .002$). Thus, based on the *OR*, the odds of near-transfer problem success were 4.40 (1.19, 18.27) times higher for students trained with HMD than for students trained with 2D simulations, and the success rates were 6.45 (1.67, 29.44) times higher for students who adopted planning than for students who did not plan. Chen, Cohen, and Chen (2010) suggested 1.68 (small), 3.47 (medium), and 6.71 (large) as cutoffs for interpreting the size of the *OR*. Therefore, the significant interaction effects had medium sized effects on problem-solving performance. However, we found no other association between the type of media or planning and problem-solving success in the second training problem or in the far-transfer problem.

3.3. Questionnaire survey results

Table 3 reports the means and standard deviations for sense of presence, self-efficacy, perceived simulator acceptance, mental workload, and simulator sickness. The two HMD groups ranked higher on the five questionnaire constructs than their 2D simulation counterparts. The two-way ANOVA results further confirmed that, compared with the 2D simulation groups, the HMD groups had a significantly higher sense of presence, $F(1, 48) = 19.58$, $p < .01$, $\omega^2 = 0.27$, higher self-efficacy, $F(1, 48) = 6.23$, $p = .016$, $\omega^2 = 0.09$, higher perceived simulator acceptance, $F(1, 48) = 6.48$, $p = .014$, $\omega^2 = 0.10$, but also a heavier mental workload, $F(1, 48) = 6.47$, $p = .014$, $\omega^2 = 0.10$ and more simulator sickness, $F(1, 48) = 8.16$, $p = .006$, $\omega^2 = 0.12$. Therefore, all the significant main effects on the subjective non-cognitive variables showed medium-to-large sized effects. In contrast, there was no significant difference between the groups with and without planning intervention or any interaction effect for all five questionnaire constructs.

Table 3. Means and standard deviations for the questionnaire survey results

	Media						
	HMD		2D simulation		Media	Method	Interaction
	With planning	Without planning	With planning	Without planning	*p* value	*p* value	*p* value
Sense of presence	4.20 (0.50)	4.22 (0.62)	3.40 (0.70)	3.49 (0.65)	$< .01^{**}$	.756	.824
Self-efficacy	4.08 (0.67)	3.64 (0.57)	3.49 (0.88)	3.23 (0.74)	$.016^{*}$	.090	.656
Perceived simulator acceptance	4.22 (0.44)	4.28 (0.59)	3.86 (0.55)	3.88 (0.54)	$.014^{*}$	.796	.877
Mental workload	3.56 (0.79)	3.21 (0.80)	2.87 (1.05)	2.51 (1.22)	$.014^{*}$	.193	1.000
Simulator sickness	2.28 (0.57)	2.36 (0.84)	1.71 (0.51)	1.85 (0.74)	$.006^{**}$	.589	.892

Note. $^{*}p < .05$; $^{**}p < .01$.

3.4. Open-ended question responses

Table 4 summarizes the reasons participants in the two HMD groups gave for favoring either HMD-supported immersive learning or conventional learning. The most frequently mentioned reasons for preferring HMD was its immersive practice opportunities (10 respondents). For example, "I prefer the HMD environment because it creates an immersive experience without a real lab and creates motivation for learning" (Respondent #4). Many participants also mentioned ease of learning as a major reason for preferring HMD (five respondents). For example, "this way simulates real experiments to a great extent, and avoids the equipment problems of real electrical circuit operations. The experimental result is clearer and it's easier to learn" (Respondent #14). Other reasons mentioned were the better learning effects (three respondents) and higher learning efficiency (three respondents) when using HMD. For example, "I can easily identify my learning issues and figure out the solution, which helps me to memorize and understand knowledge in a deeper way" (Respondent #7). The main reason given for preferring a conventional learning approach was that practice in a laboratory feels more real (four respondents). For example, "I like the lab environment, because I can learn how to operate in a real situation and learn the principles of electrical circuits more clearly" (Respondent # 40). Overall, HMD was more popular than conventional learning.

Table 5 presents the pros and cons of HMD-supported immersive learning according to the participants in the two HMD groups. Nine positive and seven negative aspects of HMD emerged in the feedback. The most frequently mentioned advantage of HMD was its authentic learning contexts (eight respondents), followed by its overcoming the constraints imposed by access to laboratories and materials (seven respondents), ease of learning (seven respondents), and the fun of learning through HMD (five respondents). For example, HMD "simulates the operation of a real experiment and allows experiential learning of knowledge" (Respondent #14); "convenient; we can have many choices, while lowering the cost in terms of time, space, and money" (Respondent #16); and "very interesting!" (Respondent #3).

Table 4. Main reasons for preferring either HMD-supported immersive learning or conventional learning

Immersive learning	Freq.	Conventional learning	Freq.
Immersive practice opportunities	10	More real	4
Easy to learn	5	Better for learning conceptual knowledge	2
Better learning effects	3	More convenient for operation	2
Higher learning efficiency	3	More familiar	1
Safer way of learning	2		
More interest in learning and higher motivation	2		
More engaged in learning	1		
Saves resources	1		

However, the participants were also concerned about eye discomfort (seven respondents), a less real experience than laboratory practice (six respondents), unstable positioning tracking (five respondents), and heavy equipment (five respondents). For example, "sometimes I feel uncomfortable when using it for a long period of time" (Respondent #6); "but still there is a sense that it is not real, because sometimes I find the image is unstable or vibrating when moving or staying still" (Respondent #11); "we do not need to go to the lab, which is more convenient, but the experience of HMD is not as good, and our vision becomes blurred and it requires more effort to learn" (Respondent #38); and "manipulation using handheld controller is not real enough, and the head-mounted display is too heavy" (Respondent #16).

Table 5. Main reasons for preferring either HMD-supported immersive learning or conventional learning

Pros	Freq.	Cons	Freq.
Experience authentic learning contexts	8	Eye discomfort	7
Overcome the constraints of access to labs and materials	7	Less real than lab practice	6
Easy to learn	7	Unstable positioning tracking	5
Fun	5	HMD is heavy and not very user-friendly	5
Practice-based learning	3	Not a wireless device and not safe	3
Flexible to operate	3	High cost and not easy to scale up	2
Better learning outcomes	2	Not real and may cause VR addiction	2
Just-in-time feedback	1		

4. Discussion

4.1. Effects of HMD and planning on problem-solving performance

The main findings partially confirmed our hypotheses that HMD and planning interventions help students to perform better in electrical-circuit design tasks and to transfer the knowledge to real-world settings. The HDM groups had higher success frequency and performed more efficiently than the 2D simulation groups in all four problems. Meanwhile, the groups that engaged in planning had better performances than groups that did not plan. Even for problems that showed no significant differences between groups, the descriptive statistics suggested a general trend in favor of HMD and planning interventions. Overall, the results supported the effectiveness of HMD and planning strategies for learning electrical-circuit design. The findings suggest that well-structured HMD-based simulation learning is a promising approach for use in various practical fields of engineering education.

Moreover, planning strategy having a larger effect than immersive media corroborated the argument that complex problem solving demands high regulative capacities of learners, which is one the paramount concerns in discovery learning (de Jong et al., 1998; Unterrainer & Owen, 2006). Whereas, immersive VR extends traditional discovery learning through offering high fidelity representation and a more rich and natural way of interaction, which supports knowledge understanding and knowledge construction but is better to be integrated with theoretically sound instructional strategies (Meyer et al., 2019). Therefore, our study reinforced Fowler's

(2015) position that immersive learning experience can be embedded within face-to-face instruction or real lab practice through rigorous learning design.

4.2. Effects of HMD and planning on the transfer of learning

It is especially intriguing to find that the HMD groups performed more efficiently than the 2D simulation groups in the post-transfer test involving real-world tasks, although there were no significant differences in the performances in the simulated training environments. This is consistent with previous studies showing that the user control afforded by HMD environment results in better transfer results (Gegenfurtner, Quesada-Pallarès, & Knogler, 2014), perhaps because HMD-based simulation environments allow users to naturally move their bodies, for example to walk, move their heads, grab or navigate some objects, which allows them to positively control the information received during the experience which, in turn, strengthens embodied learning (Hsu, Tseng, & Kang, 2018).

However, unlike a previous study (Meyer et al., 2019), we found no interaction effect between media and instructional design, perhaps because the participants in the non-planning groups performed some implicit planning even without a purposeful thinking-aloud process. Another possible explanation is that participants in the HMD groups had a heavier mental workload than those in 2D simulation groups, and planning made had no significant effect on reducing their workload. Further studies are needed to determine which type of workload, intrinsic, external, or germane load, occurs in simulation environments and under what conditions, so as to provide more effective contingent scaffolding in HMD-based learning environments (Makransky et al., 2019b). We elaborate on the workload issue in HMD in the next section.

4.3. Perceptions of HMD in support of problem solving

The students' opinions of the usefulness of HMD for learning were consistent with those identified in previous studies (Concannon et al., 2019; Makransky et al., 2019a) including both positive aspects, such as sense of presence, self-efficacy, simulator acceptance, and negative aspects, such as simulator sickness and mental workload. Their feedback on present feeling, simulator acceptance, and mental workload suggested that the visual representations in HMD and WIMP (window, icon, menu and pointer) in 2D simulation may have different effects on the learning experience (Barricelli, Gadia, Rizzi, & Marini, 2016; Jin & Lee, 2019). Further, according to participants' feedback, HMD was especially suitable for cultivating interest in learning and provided adequate opportunities for practice with just-in-time feedback, which is critical for novice learners to establish problem-solving confidence. Regarding the benefits of cultivating learning interest, supporting learning engagement, and improving self-efficacy in introductory electrical circuit design, the novel approach seems ideal for pre-service STEM teacher training for the learning experience may influence their future teaching practice.

However, they also expressed major concerns with HMD's technical flaws, such as eye discomfort, heavy equipment, and imperfect positioning tracking stability. Although HMD seems to be a better simulation environment than desktop 2D, some learners preferred to practice in a real laboratory. The divergent learning perceptions of using HMD implies whether to adopt the HMD-based problem-solving learning is not simply a yes/no question. This field deserves future research with respect to cost-effectiveness analysis regarding the adoption of HMD in electrical circuit design, as well as exploring innovative approach of integrating desktop simulation, HMD-based simulation with real lab experiments to optimize the benefits from different learning technologies.

The obvious perception of a heavy mental workload in HMD groups can be explained by the challenge of integrating conceptual knowledge, procedural knowledge, and psychomotor skills. For example, if learners received feedback from the HMD environment indicating a problem with their circuit solution, they had to scrutinize the circuit and reflect on their conceptual knowledge in the circuit design, generate troubleshooting strategies to locate the malfunctioning part of the circuit, orient the breadboard, and examine the connectivity of the electrical components to rule out the possibility of an open/short circuit. Such a reality-based interaction process demands a much higher comprehensive competence than 2D simulation. However, as Jost et al. (2019) have argued, this can be beneficial for building an intrinsic cognitive load in electrical engineering education, for the training goal is to perfect the cognitive processes and psychomotor skills in electrical design, wiring, testing, and troubleshooting.

5. Conclusions

This study investigated the effect of HMD and planning on problem-solving-based learning. In general, students who learned through HMD performed better than those who learned through 2D simulation, and students who adopted a planning strategy performed better than those who did not, although in some cases, the results failed to reach statistical significance. In addition, HMD-based learning induced a higher sense of presence, self-efficacy, and simulator acceptance than 2D simulation learning. However, the former media intervention also led to a heavier mental workload and more simulator sickness than the latter. In addition, although physical ergonomics of HMDs has improved a lot since its inception, technical problems related to wearing comfort, visual quality, positioning tracking and natural interaction were still a major concern for the learners. These findings imply that HMD is not a panacea that can support all levels of learning or that can replace laboratory-based problem-solving practice; however, it is a promising complement to the traditional way of learning disciplinary problem solving (Jaakkola et al., 2011). Besides, the study suggests HMD can be useful learning technology for similar disciplines like electrical engineering that requires hands-on practice to help students align domain knowledge with psychomotor skills. But it is also necessary to further address the side-effects of HMD-based learning, such as mental workload and simulator sickness, and to develop effective instructional strategies in immersive learning contexts.

This study has several limitations. First, it should be pointed out that the small sample size of this study limits the strength and generalization of the results; nonetheless, it does give a first glimpse on understanding the impacts of HMDs in problem-solving-based learning. Second, it would be worth investigating the problem-solving behavioral patterns of using head-mounted displays, such as eye movement, to increase our knowledge of mental workload in immersive virtual reality. Third, although 2D simulators are common in this field, and most have similar functionality and have been widely adopted in electrical engineering education, we only found one comparable HMD application in this field, and the functionality of these two simulation tools might not be exactly the same, such as types of electrical elements and circuit simulation feedbacks. To make sure the two simulation tools can provide the same constraints and functions, the problem-solving tasks were carefully selected and tested in both simulation conditions by a subject teacher. Finally, the long-term effects of HMD on the development of problem-solving competence needs to be investigated via a longitudinal study in the future.

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Appendix 1

Construct	Items	Source
Sense of presence	1. I could easily engage into this simulation environment. 2. I was very engaged in solving the circuit design problems and barely noticed anything around me. 3. I focused on completing the problem-solving tasks and did not realize the passage of time. 4. I had a feeling of being in a circuit lab.	(Witmer & Singer, 1998)
Self-efficacy	1. I believe I can complete the task of circuit design experiment. 2. I believe I have developed good knowledge and skills for completing circuit design experiments. 3. I believe I have mastered the knowledge and skills of circuit design experiments.	(Meluso et al., 2012)
Mental workload	1. I can operate freely when I conduct a circuit design experiment in the simulation environment. 2. I can easily complete the circuit design task in the simulation environment. 3. I don't need to remember or think too much when I work on the problems in the simulation environment. 4. I am more relaxed in the process of completing the experiment in the simulation environment.	(Hart & Staveland, 1988)
Simulator sickness	1. I often feel unwell throughout the circuit design task in the simulation environment. 2. I often feel dizzy throughout the circuit design task in the simulation environment. 3. I often feel blurred vision throughout the circuit design task in the simulation environment.	(Davis, 1989), (Venkatesh & Bala, 2008)
Simulator acceptance	1. The simulation environment can help me learn electrical circuit design. 2. The simulation environment makes it easier for me to understand problem-solving task as well as to learn task-related knowledge and skills. 3. I am satisfied with circuit design study in the simulation environment. 4. I am more interested in learning circuit design through the simulation environment. 5. I am willing to learn relevant knowledge and skills in such a simulation environment in the future.	(Kennedy et al., 1993)