# Circuit Learning in A Virtual Environment

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## 1 INTRODUCTION

For years, online education has been experiencing a surge in popularity. Between 2012 and 2019, the number of hybrid and distance students rose by 36 percent. With the advent of the COVID-19 pandemic, the number of remote students nearly tripled [4, 8]. Despite the convenience of online learning, online students do not have access to all of the same learning resources that are available to their in-person counterparts, thus resulting in an educational gap for a significant population of learners. Nevertheless, studies have shown that students can effectively learn in virtual environments, even without the presence of an instructor [27]. Educational video games have emerged as a promising tool for enhancing virtual learning outcomes, particularly those that provide relevant educational content [23]. Utilizing game mechanics to integrate learning content can provide effective outcomes, but the amount and format of information presented determines what information is perceived to be important [36]. For instance, linking the content directly to the relevant object can help a student to comprehend the information's relevance in context [3, 33]. However, the effectiveness of other annotation styles remains uncertain and further research is required to establish their value [33]. Screen-fixed and world-fixed are two types of annotation styles, where the annotation either remains in a fixed position on the user's screen or is linked to an object within the virtual world [5]. Research has been done on the effectiveness of different annotation positions, finding that different positions are better suited for different types of tasks [5]. This project explores the effectiveness of screen-fixed and world-fixed annotation types in a virtual learning environment related to building circuitry.

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## 2 RELATED WORKS

### 2.1 Visualization of Circuits in Virtual Environments

Laboratory experiments have been a staple of science education for many years, and have been shown to facilitate learning development and problem solving skills[12]. This may be because laboratories are an effective environment for conveying conceptual change [30]. By having a hands-on experience students are more willing to accept concepts that are not intuitive. This makes laboratory experiments a valuable tool in teaching concepts like physics [39]. Studies have shown that computer-based simulations are also effective in conveying physics concepts, by creating a hands-on experience similar to real experimentation [39].Research has also shown that computer-based simulations can be successful in teaching students the concepts of circuit learning [16, 23, 31]. Virtual circuit labs can be used as effective alternatives to in-person labs for distance learning in circuitry courses, or even as supplements for parts of an in-person curriculum. A 2007 study comparing undergraduates in a physics course found that students who combined virtual lab sections into parts of their course saw a marked improvement in understanding compared to those who only used physical breadboards throughout. [40] Moreover, using virtual lab equipment allows for a drastic reduction in cost for distance learners [16, 26]. Studies have also shown that tools used for content-specific instructional guidance are positively correlated with learning performance. In particular, contextual instructional guidance in circuit learning can help students better understand and implement circuit-building concepts [23]. While AR/VR abstractions of circuit designs can be used to ease students into performing circuit construction with actual components [31]. This is valuable because working with real circuit components often requires more serious debugging. A study on virtual circuit labs found that students in a real lab can face additional frustrations because they may have a circuit with valid logic, but a combination of other factors may still prevent the circuit from performing correctly [11]. Some of these confounding factors include bad components, bad instrument settings, and power problems, which can be difficult for a student to diagnose and time-consuming for an instructor to resolve[11]. Additionally, a virtual environment has the added benefit of being able to visualize invisible phenomena, which can be particularly valuable in a physics setting [25]. The growing use of virtual laboratories has led some to question whether a virtual lab provides the same level of education to students or it is just more convenient and cost effective [7]. This question inspired a study on virtual versus physical labs in a post-secondary physics course [7]. They found that students who learned to build circuits in a virtual lab were equally competent at answering conceptual questions as their physical lab counterparts. Additionally, students who learned to build circuits virtually were equally capable of building the circuits physically. A further study based on these results also found that students who learn to build circuits virtually may have a more positive experience overall [32]. This may be due in part to there being less frustration associated with failure. In a physical lab environment, misuse of components can cause them to be damaged, which is difficult for a novice to identify. A study done specifically on the perception of students in a physical versus virtual lab environment found that students who completed the virtual lab had a more positive experience than those in a physical lab [1]. Using a virtual circuit allows students to experiment without the consequences associated with physical components. This ability to “play” in the laboratory environment led to students reporting a more enjoyable experience when learning about circuit concepts [32].

### 2.2 Efficacy of Games as Learning Tools

Commercial games often run into issues when being adapted for educational purposes [6]. Since learning objective are often imposed on commercial games, instead of being implicitly present, educators may find it difficult to keep their students focused on their intended learning goals. This has led researchers and educators to instead look toward serious games as an alternative for engaging educational content. Though there has been some debate over the specifics of what qualities serious games have. Learning can take place in different environments and with different goals, which distinguishes the circuit construction software used in a university lab from something like Gidget, which players are meant to engage with on their own time for discretionary learning [17], or even *Assassin's Creed* or *Oregon Trail* which may teach some history along the way [38]. The most commonly accepted definition is "games that do not have entertainment, enjoyment, or fun as their primary purpose," [22], However, a problem arises when trying to define serious games solely on the intentions of their developers. Since the intended purpose of a game can be unclear, and potential clarifications can be inaccessible to those who did not play a role in designing said game, it can be difficult to determine what does and does not count as a serious game [14]. In order to solve this issue, Laamarti et al. propose a broader definition, stating that a serious game is "an application with three components: experience, entertainment, and multimedia," positioning serious games squarely between computer games, sport and board games, and training simulators. [15] We intend to work with this definition of serious games for the purpose of our experiment, as it allows for elements of entertainment and gamification to be present, but education and training still lie at the heart of their design.

Laamarti et al. further split serious games up based on several key criteria, which each play a role in determining a game's efficacy:

- **Activity:** The key activities that a player performs in a serious game have a tangible impact on the effectiveness of said game's learning outcomes. A game's primary activities should match the content that is presented to the player. [15] For instance, a serious game that focuses on the user's physical fitness should justifiably teach and encourage them to perform physical activities through gameplay. [2] The same goes for games that have a heavy focus on education - instead tasking the player to engage their mental faculties in order to solve problems related to its' given domain. [28]
- **Modality:** Modality encapsulates how information is delivered to the player by the game sensorially. The three typical modalities explored by games are visual, auditory, and haptic, and choosing modalities that align with a game's purpose are important, as this can influence the effectiveness of its' educational components and overall experience. [15, 34]
- **Interaction Style:** How the user goes about interfacing with the game. In most educational contexts this takes the form of a keyboard, mouse, or gamepad, but some situations may warrant the use of other, specialized controllers if they are deemed appropriate for the game's goals. [15]
- **Environment:** Laamarti et al. additionally explain that environment, both within the game, and the real-world context that the game is played in, can have an influence on a serious game's efficacy. Whether a game can be played on mobile devices or not, and if it requires internet connectivity are both major real-world criteria that determine when and where a player is able to actually play the game. Additionally, the presence of other players in a multiplayer game can influence how a player engages with the game's content. [15] Special attention should also be paid to VR/AR implementations in serious games. The addition of virtual and mixed reality functionality can drastically change how the player interfaces with a serious game, as it further immerses them in a virtual environment, and allows them to use their own body to navigate said environment. [37]
- **Application Area:** Finally, application area refers to the various application domains that a serious game's content applies to. [15] Though most serious games have fallen under the broad application domain of "education", it's difficult to determine how effective of a teacher a game can be when being built for such a broad audience.

> While there is no doubt that most serious games teach something, they are truly effective when made with a specific audience in mind, and act not as standalone teachers, but as supplements used alongside other instructional curricula. [9]

When instead looking at the effectiveness of a serious game's contents, Wouters and Oostendorp have provided a meta-analysis on uses of instructional techniques in serious games. Relevant to us, their research has found that content integration on its own has a low-to-moderate effect on learning, and modeling had a moderate effect on learning in isolation [36]. *Content integration* involves learning content being integrated with game mechanics. Though their definition varys noticeably from Laamarti et al.'s, Wouters and Oostendorp define *modeling* as "an explication or indication how to solve a problem. The explanation can be given by a peer or expert and can be verbal, animated, or graphical." [36] Both aspects engage with cognitive processes of selection and organization/integration. The modeling aspect of annotations is our primary focus - we want to examine if the form of annotation has an effect on learning. Given that this form of instructional technique had a moderate learning effect (effect size measure: d=.55) with a p-value of < .001, we hope this will be observable through our experiment. Content integration, while less effective overall, will be implicitly included, given the nature of our methodology.

In their meta-analysis, Wouters and Oostendorp additionally break the implementation of serious games into three main pairs of competing goals: learning versus playing, drill & practice versus microworlds, and transmission versus construction.

- **Learning vs. Playing:** Most games meant for commercial consumption have mechanics and goals that interfere with their potential uses as learning tools. Educators attempting to use commercial games for educational purposes will likely run into situations where the game's functionality is in dissonance with and distracts from their intended learning objectives [6].
- **Drill & Practice vs. Microworlds:** Within the realm of edutainment games, "drill & practice" styles of gameplay, which pare down the scope to the bare essentials of conveying concepts and subsequently "drilling and practicing" on said concepts using systematic repetition, have been shown to be effective given their straightforward nature [6] [18]. However, on its own, this rigid style of game lacks the benefits that other forms of teaching provide. Only by combining it with other forms of teaching can this style of game be at its most effective. When advancing through levels with a learning curve, there will always be problematic levels and cases where students need extra support to transfer between the game and what they know [24]. Our annotation styles may be a promising tool for those cases.
- **Transmission vs Construction:** Games offer a unique learning environment in microworlds they create, where learning material can be constructed from pieces immersed in the game rather than being drilled in with direct transmission. However, to avoid divorcing educational concepts from their real-world implementations in a microworld approach, a teacher is required to oversee the activities and ensure the transfer of knowledge happens [6]. A direct transmission of the knowledge still has its own challenges with exercising the applications of knowledge outside the game when it is poorly integrated into the game's mechanics [10].

With all of this in mind, we decided to err on the side of caution when developing our methodology. We decided that our game environment would be primarily focused on learning, rather than gameplay, with a strict level-based structure. However, within the confines of the game, users would still have the ability to engage in play with the tools we afforded them. Though gameplay would be abstracted from real-world practice, we wanted to ensure that our methodology would retain a clear analogy to how circuits are built in the physical world.

### 2.3 Annotations in Virtual Environments

Intelligent tutoring systems can yield the best learning outcomes when they provide detailed, immediate feedback to their students. Though this has been established as a best practice for the genre since around 1993, it's not always easy to implement in every tutoring system or "serious game" [29]. This topic will be discussed further in a later section, but annotations offer a variety of quick and accessible options for that feedback, and can facilitate learning by guiding the student to relevant information [33]. Previous work [5] has been done comparing the effectiveness of annotations based on their placement in a virtual environment. Screen-fixed annotations are annotations that are anchored to the display, while world-fixed annotations are annotations that occur within a virtual environment and are attached to objects within that environment [5]. Other setups that separate information across the user's field of view are also possible, especially on multiple displays or head-mounted devices, but users show a fairly strong preference for interfaces that keep all the information they need at roughly the same depth and in the same field of view [19]. Between screen-fixed and world-fixed on the same display, neither annotation type has been shown to be superior at facilitating learning, but there does appear to be an interaction between annotation type and the level of information that can be provided. Annotations can be used to provide explanations, instructions and illustrations, but have the largest effect on success when they contain an explanation relevant to the topic. In a 2010 study about circuit learning, prompts explaining the principles involved in each circuit and component increased users' understanding further compared to simple correct or incorrect feedback. [20]. Another user study in a healthcare setting, with tooltips added to an existing software for patient records, compared users' stated preference in interviews to their error rates. The tooltips contained either a definition and explanation for each field or just an expected range of values, and though users stated a preference for the range, their error rates were lower with the longer explanations. This highlights that the relationship between what users think works and what actually works can be complicated, and emphasizes the importance of comparing user questionnaires and confidence ratings with their performances instead of relying on just one kind of data [13]. Another factor that can't be ignored, whether in a learning environment or any other kind of software, is the simple amount of space available on the screen - more annotations, explanations, and hints always come at the cost of readability. Adding more information in an educational context may push the proper balance a little further towards clutter, but the trade-offs should still be considered [35].

## 3 METHODS

### 3.1 Participants

The participants in this study were undergraduate students enrolled at a public university in the United States as well as friends and family of the researchers. They students were all enrolled in a senior-level capstone course in Computer Science. Of the 85 students registered in the course, those participating were randomly separated into two equal groups: one for each annotation method. Prior experience with circuits was not controlled for. This prior knowledge was determined by giving each participant a survey.

### 3.2 Materials

The circuit-build environment participants interacted with was created in the Unity game engine. We developed 3 levels for participants to complete, with implementation inspired by Schackasawa's Project Faraday, a more robust circuit-building environment for virtual reality.

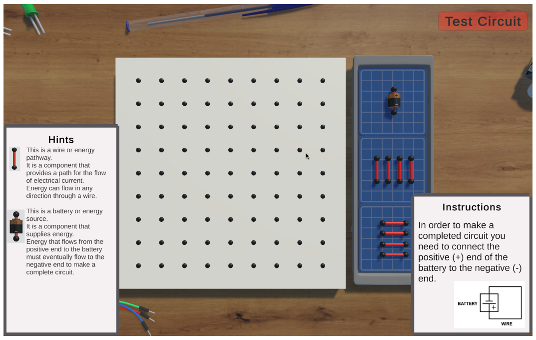


Fig. 1. Screen-Fixed Annotations

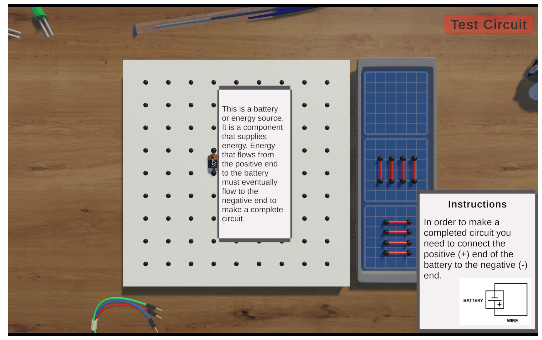


Fig. 2. World-Fixed Annotations

Participants interacted with a top view of a board of nodes that components snapped to. Using this interface, circuits can be built to complete the levels from basic parts like wires, batteries, and lights. This idea of an array of nodes was selected based on Project Faraday.

The two annotation types were implemented as a sidebar for the screen-fixed approach and a popup for the world-fixed one. The screen-fixed sidebar can be opened and closed using a button in the top-right corner, and it displays information for all components in one window. World-fixed popups are displayed when hovering over a component with the mouse, and it displays relevant information for that specific piece. Both the sidebar and popup provide the same information verbatim.

### 3.3 Procedure

Before beginning the study, participants were asked to complete an informed consent form. After consenting, they were given a demographics survey and a Likert scale survey, asking about their confidence in building circuits. At the top of the pre-experiment survey they were assigned a Participant ID and a group letter. Group A used screen-fixed annotations 1 and Group B used world-fixed annotations 2.Before beginning the study, the participant watched a video that explained the goal of the study and walked through the controls and how components could be moved to the circuit board. We chose to include an introductory video because pre-training has been shown to have a positive effect on learning outcomes [21].

After completing the video the participant entered their ID and selected a button to begin the first level. When the level started the program recorded the beginning time. In this level the participant had to build a circuit using a battery and a wire. When the participant successfully completed the circuit they were notified with a popup and the program recorded the completion time. The participant completed a second level using a battery, wire and a light bulb. The start and finish times were recorded again for the second level. The final level included using a battery, wire and two light bulbs.

After completing the study, each participant was given the same Likert scale survey asking about their confidence completing circuits.

### 3.4 Design

The study was a 1-factor between-subjects design, where both groups were given the same circuit-building levels to complete with the same information provided in annotations, verbatim. One group received these annotations in a screen-fixed sidebar that presented all component information in once place 1, and the other group received the information related to a component when hovering over it with the mouse 2.

For every trial, the time to complete the circuit-building levels was recorded using a clock in the software, recording when each level began and when it was successfully completed. The time was paused during level transitions, only measuring how long the problems themselves take. Participants' confidence was measured using a Likert scale question, used both before and after the experiment. Each question ranges in 5 responses: do not know, not confident, somewhat confident, and fully confident.

## 4 RESULTS

In order to determine which type of statistical test would be the most valuable for the data set, Shapiro-Wilks tests were done on the interval data (Completion Time). The results, shown in Table 1, did not hold to normality under all circumstances; Level 1 and Level 3 showed significant deviation from normality ($p > .05$). Because the data was not normally distributed, a Mann-Whitney U test was employed.

Table 1. Normality Tests (Shapiro-Wilk)

| | | W | p |
|---|---|---|---|
| Level 1 Completion Time | A | 0.965 | 0.836 |
| | B | 0.694 | < .001 |

| | | W | p |
|---|---|---|---|
| Level 2 Completion Time | A | 0.874 | 0.110 |
| | B | 0.954 | 0.711 |

| | | W | p |
|---|---|---|---|
| Level 3 Completion Time | A | 0.666 | < .001 |
| | B | 0.630 | < .001 |

| | | W | p |
|---|---|---|---|
| Total Completion Time | A | 0.748 | 0.003 |
| | B | 0.832 | 0.036 |

Because the data was not normal, we chose to conduct a Mann-Whitney U test. The Mann-Whitney U test tests if there is a difference between two independent samples for a non-normal population by comparing the rank sums of two groups. In our case, the two groups are Group A (screen-fixed annotations) and Group B (world-fixed annotations). The population size for Groups A and B was 10 participants each ($N = 20$). Our null hypothesis is that the rank sums of Group A and Group B do not differ significantly, meaning that the average level completion time for the groups do not differ significantly.

Below are the results of the Mann-Whitney U test on the completion time for each level:

Table 2. Independent Samples T-Test (Mann-Whitney U)

| | W | df | p |
|---|---|---|---|
| Level 1 Completion Time | 61.000 | | 0.436 |

| | W | df | p |
|---|---|---|---|
| Level 2 Completion Time | 67.000 | | 0.218 |

| | W | df | p |
|---|---|---|---|
| Level 3 Completion Time | 61.000 | | 0.436 |

| | W | df | p |
|---|---|---|---|
| Total Completion Time | 62.000 | | 0.393 |

The results of the Mann-Whitney U tests show that difference between Group A and Group B, with respect to the completion time, was not statistically significant ($p > .05$), therefore the null hypothesis cannot be rejected. We will use these p-values to make inferences about our results.

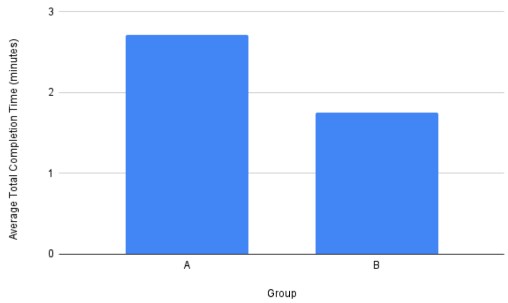


Fig. 3. Average Total Completion Time Between Group A and B

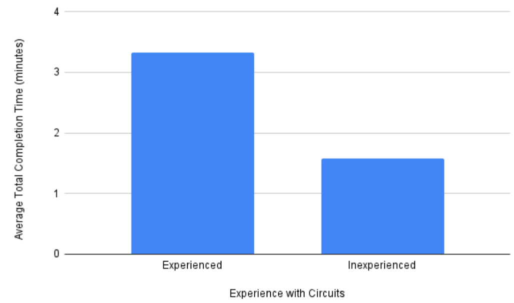


Fig. 4. Average Total Completion Time by Experience with Circuits

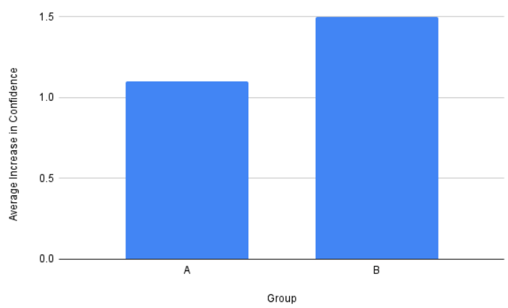


Fig. 5. Average Increase in Confidence Between Group A and B

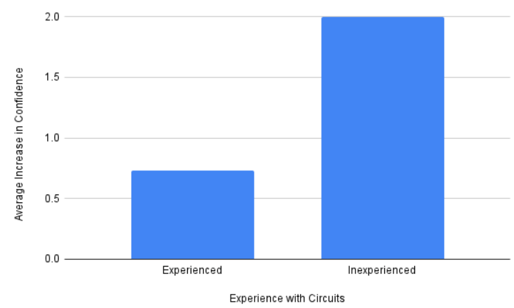


Fig. 6. Average Increase in Confidence by Experience with Circuits

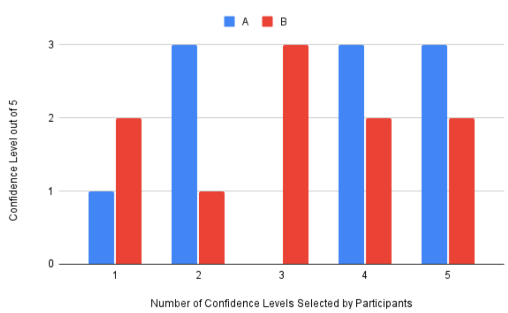


Fig. 7. Confidence Levels Selected by Participants Pre-Experiment

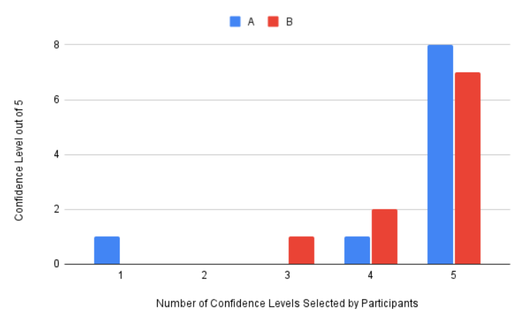


Fig. 8. Confidence Levels Selected by Participants Post-Experiment

## 5 DISCUSSION

Ultimately, we were unable to reject the null hypothesis of our experiment. This means that there was no significant difference between the completion time for screen-fixed and world-fixed annotations. While there was not a significant difference between the completion time of the groups, Group A (screen-fixed annotations) completed the levels at a slower rate than Group B (world-fixed annotations) (Figure 3). There was additional data collected from the participants in the form of a pre- and post-experiment survey. These surveys asked the participants some demographic questions as well as three Likert scale questions on their confidence in working with circuits.

Overall, there was an increase in confidence shown between the pre-experiment survey and post-experiment survey (Figures 7, 8). However, there was a single participant who showed a decrease in confidence after completing the experiment. This result may be explained by the Dunning-Kruger effect, in which a person overestimates their ability to complete a task. When considered by annotation type, the participants who used world-fixed annotations showed a greater increase in confidence than those who used screen-fixed annotations (Figure 5). Additionally, participants who were inexperienced with circuits showed a greater increase in confidence after completing the experiment than those who had previous experience (Figure 6).

One additional interesting observation was that participants who had prior experience with circuits took more time to complete on average than inexperienced participants (Figure 4). This may be due to the fact that participants with experience were more likely to experiment in the environment, rather than just completing the assigned task.

## 6 CONCLUSION

The findings of this study did not provide sufficient evidence to reject the null hypothesis. Thus, we support the hypothesis that there is no difference in measurements of learning between screen-fixed and world-fixed annotations in regards to assisting virtual circuit learning. While we cannot support our proposed alternative hypothesis, our inconclusive evidence can help inform future research and contribute to a better understanding of the topic at hand.

One such avenue of research is to conduct a similar experiment using alternative measures to assess learning outcomes. This may provide additional insight into the effectiveness of both annotation types. Through our research we came to understand that different types of annotations vary in effectiveness by according to the nature of the information displayed. Further research could be done by enacting the same experiment with more challenging material. Such as advanced circuitry. Further research could also be valuable in establishing the net benefit of annotations as a baseline. Our experiment does not include a version without annotations, meaning there was no group to control against. Research comparing an experience with and without annotations could result in interesting learning outcomes.

Overall, while our study did not produce conclusive results, it contributes to the dialogue surrounding virtual learning outcomes and the roles that annotations types have therein.

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