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Evaluating the Impact of the Physical Fidelity of the Learning Environment on Skill Acquisition, Retention, and Application

Myrtede Alfred
Clemson University, malfred@g.clemson.edu

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EVALUATING THE IMPACT OF THE PHYSICAL FIDELITY OF THE LEARNING ENVIRONMENT ON SKILL ACQUISITION, RETENTION, AND APPLICATION

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by
Myrtede C. Alfred
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Accepted by:
Dr. David. M. Neyens, Committee Chair
Dr. Anand Gramopadhye, Committee Co-chair
Dr. Joel Greenstein
Dr. Marissa Shuffler-Porter

ABSTRACT

Simulations are believed to support learning outcomes by increasing student engagement and providing a more immersive and interactive learning environment. Research into the effectiveness of simulations as learning tools has found tangible benefits, including increased learner engagement and conceptual gains. Simulations also offer the benefits of a safer and more accessible learning environment, where students can practice until the point of proficiency. While simulations have been used extensively in workforce education, there is limited research that compares learning outcomes – affective, skill-based, and cognitive - when learning in the physical environment is substituted with learning in a simulated environment, particularly for technical skills. Educators and researchers have questioned whether simulations provide learners with the same quality of education as learning in a physical environment. Simulations lack the nuances that exist in the real world and may also oversimplify a complex system. Its ideal representation of a system may create issues for learners when they encounter issues in the real world environment that they never experienced in the simulation. Consequently, learners may doubt that the principles demonstrated in a simulation are applicable in the real world. Proponents of physical laboratories argue that simulations limit students from experiencing hands-on manipulation of real materials and that they lack the necessary detail and realism to effectively teach proper laboratory technique.

This research works to fill this gap by investigating how individuals transfer learning in simulated environments to the real world. Affective, cognitive and skill-based learning outcomes were used to evaluate acquisition, transfer and retention. There are three primary aims of this research. The first aim was to identify how the physical fidelity of the learning environment impacted learning outcomes, including transfer, and whether the goal orientation and cognitive ability of the learner influenced the relationship between the physical fidelity of the learning environment and learning outcomes. The second aim of this research was to understand the mechanisms through which the physical fidelity of the learning environment impacted proficiency outcomes**.** The third aim of the study was to understand how the physical fidelity of the learning environment impacted retention. The findings from these aims offer substantive contributions about how simulations affect learning, transfer, and retention outcomes. This research has implications for the design and implementation of simulated environments in engineering and technical disciplines, specifically courses delivered in an online setting. Whether positive or negative, these results can help identify potential issues and provide insight on what aspects of the transition from learning in simulations to working in the real world create the greatest stumbling blocks for students.

DEDICATION

To my mom, Marie Emmanuela Deloudres Alfred, for instilling us with the value of education. To my dad, George Alfred, for working more hours than there are in a day to support us. To my siblings – Rico, Andy, Jerry, Marco, Cleo, Tania, and Tash – for your unshakeable faith in me. To my many nieces and nephews for keeping me young. And to my nephew Johnny (Junior) and everything he would have achieved.

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CHAPTER ONE

INTRODUCTION

The use of technology has led to unprecedented changes in secondary, higher, and workforce education. For example, virtual schools enable high school students to earn their diplomas online, and, similarly, online degree programs have become increasingly more commonplace in higher education. In the professional world, organizations leverage online courses and webinars to provide their employees with continuing and just-in-time educational opportunities. This learning environment, which has historically been defined as having a delivery mechanism with at least 80% of the course content delivered online, has evolved significantly over the past decade (Kentor, 2015). Early platforms were primarily asynchronous, utilizing chatrooms and discussion boards. Now it is common to see synchronous online education with instructors holding lectures and discussion in virtual classrooms.

Online education has also been highly effective in increasing educational opportunities for students, particularly nontraditional students who, for example, are older, attend school part-time, or are financially independent (Allen & Seaman, 2007). In addition, it has frequently focused on such conceptual programs as MBAs, public administration, and education programs (Allen & Seaman, 2006). On the other hand, engineering and other technical fields have lagged behind other disciplines in using online delivery for course and laboratory instruction (Bourne, Harris, & Mayadas, 2005). Because presenting such technical course material in an online setting necessitates adaptation, it is important to develop and subsequently evaluate online education technologies and pedagogies to ensure they are effective in imparting technical skills (Bernard et al., 2004). Identifying whether these technical and hands-on tasks can be effectively learned in simulated environments is an important first question that needs to be addressed before expanding course offerings in online education.

More specifically, designing effective simulated laboratories is instrumental in supporting the development of a robust online engineering, science and technical curriculum as such instruction is a key educational component in these disciplines. Laboratories were initially developed with the belief that understanding how to apply science to solve real world problems requires both theory and practice (Auer, Pester, Ursutiu, & Samoila, 2003). As a result, their instructional space focuses on demonstrating laboratory techniques, developing analytical thinking and connecting theory to practice for students (Woodfield et al., 2005); thus, using the physical equipment and components during instruction represents the highest level of physical fidelity with the actual working world as physical laboratories provide students with the opportunity to experience the sensory characteristics of the tools and components and, in some instances, learn in an environment closely corresponding to that in which they will be used (Zacharia, 2007; Zacharia & Olympiou, 2011). Additionally, such physicality, i. e. the actual manipulation of physical material, is believed to be important for learning (Zacharia & Olympiou, 2011).

Although simulated laboratories are increasingly used in science and engineering education (Gillet, De Jong, Sotiriou, & Salzmann, 2013), they have been primarily employed to supplement classroom education (Finkelstein et al., 2005), not as standalone educational delivery systems. These laboratories provide several advantages over physical ones, including creating a safe environment that allows learners to practice at their own pace and on their own schedule until they reach the point of proficiency (Krueger, 1991; Zacharia, 2007). Just as important, simulated laboratories can also be delivered in an online setting that allows increased diversity and access to higher education, increased efficiency of delivery, and improved personalization of the learning process (Henderson, Selwyn, and& Aston, 2015). In addition, simulations can support learning outcomes by increasing student engagement and providing a more immersive and interactive learning environment (Adams et al., 2005). However, one issue with the use of these labs, especially for technical tasks, is whether they provide the same quality of education. Although simulations have had a long history of use in workforce education, the nature of those industries does not allow direct comparison between learning in real-world and simulated environments (Stone, 2001), in part because they have primarily been used in industries where engaging in real-world training would be dangerous, expensive, or potentially unethical.

The research comparing learning outcomes between the physical and simulated environment is limited, particularly for technical skills. The majority of the studies investigating learning in 2D and 3D simulations have focused on conceptual gains, with none specifically evaluating transfer and retention outcomes (Campbell et al., 2002; Finkelstein et al., 2005; Zacharia, 2007; Zacharia & Olympiou, 2011; Jaakola, Nurmi, and Veermans, 2011). In this context, learning is defined as the acquisition of knowledge following a period of instruction, while retention refers to the length of time it is remembered and transfer indicates the ability of students to apply their knowledge outside of the learning environment (Baldwin & Ford, 1988). The research reported here seeks to understand whether individuals who learn a technical task in a 2D or 3D simulated environment achieve comparable learning, transfer, and retention outcomes as those who learn in a physical environment. The comparison of 2D and 3D simulations is particularly novel as the studies evaluating the influence of increasing fidelity on learning outcomes is limited. Fidelity in this context refers to the degree which a virtual or simulated environment corresponds to the real world (Alexander, Brunye, Sidman, and Weil 2005).

As the effectiveness of technology in relation to learning outcomes is also influenced by learner characteristics such as cognitive ability and prior knowledge, this research investigates these attributes on learning, retention and transfer. In particular, learner characteristics impact learning strategies, effort, and perseverance (De Raad & Schouwenburg, 1996), attributes that can subsequently influence the effectiveness of an instructional program as well as its learning outcomes (Anderson, 1982; Noe, 1986; Snow, 1989). While there are many characteristics which can potentially influence learning and transfer outcomes, this study focused on goal orientation, engagement, and cognitive ability. Currently, there is limited research investigating the possible moderation effects of these characteristics on the relationship between fidelity and the various outcomes.

Both simulations and physical instruction have benefits and disadvantages. The impetus for exploring whether a technical curriculum can be effectively learned in simulated environments stems from both the increasing use of technology in education and the educational opportunities it can create. The overall goal of this research is to provide insight in terms of what design characteristics are important for developing effective simulations for lab instruction and how institutions can support this form of instruction.

Research Aims

More specifically, this research investigating learning, transfer, and retention outcomes for participants learning at different levels of physical fidelity involves the following three primary aims:

- *Aim 1: Identify how the physical fidelity of the learning environment impacted skill acquisition and transfer and determine whether the goal orientation and cognitive ability of the learner moderated these relationships.* This aim was assessed using an experimental study that compared learning outcomes among participants learning to construct a circuit on a breadboard under three different levels of physical fidelity: a 2D simulation, a 3D simulation, and physical components.
- *Aim 2: Identify how the physical fidelity of the learning environment and the transition from the simulated environment to the physical environment contributed to differences in the learning outcomes achieved by the participants.* This aim was evaluated by interviewing a representative sample of participants from the first study about their experiences learning under different levels of

fidelity and their transition from the simulated environments to the physical environment.

- *Aim 3: Evaluate how the physical fidelity of the learning environment impacts retention*. This aim was examined using an experimental study that compared retention outcomes at the 2-week and 4-week intervals among participants learning to construct a circuit on a breadboard using a 2D simulation, a 3D simulation, or physical components.

These research aims will provide insights about the effects of physical fidelity on learning, transfer, and retention outcomes. Prior to developing the studies to evaluate these aims, a comprehensive literature review was conducted to gain the context and information needed to thoroughly understand the research area. Chapter 2 discusses the relevant literature concerning laboratory instruction and the use of 2D and 3D simulations in laboratory instruction, specifically in science and engineering. Goal orientation and cognitive ability and their influence on these outcomes were also reviewed. The third chapter discusses the initial dissertation experiment evaluating the influence of physical fidelity on learning and transfer outcomes, while the fourth chapter describes the qualitative analysis conducted to determine how the transition from the simulated environments to the physical environment contributed to the learning outcomes achieved by participants, and the fifth chapter discusses the last study which evaluated the effect of the physical fidelity of the learning environment on retention. The final chapter discusses conclusions, broader impacts, and potential areas for future research.

CHAPTER TWO

LITERATURE REVIEW

This literature review focuses on research on the impact of the physical fidelity of the learning environment on learning, retention and transfer outcomes within the larger instructional model and how this relationship may be influenced by specific learner characteristics. It is organized into two sections: (a) the impact of physical fidelity on instructional (learning and retention) and transfer outcomes and (b) the impact of learner characteristics on instructional and transfer outcomes. Baldwin and Ford's model of training transfer is introduced first as it was the primary conceptual model used in this research and because it served as a means to organize the research analysis and to discuss the study findings.

Conceptual Model of Transfer

The most commonly cited model of transfer, the one developed by Baldwin and Ford (1988), describes its goals in terms of the instructional and transfer outcomes as seen in Figure 2.1. Its instructional outcomes include the learning and retention of knowledge or a skill, while transfer outcomes include generalization, defined as the application of a skill outside of the learning environment, and maintenance, which is the continued use of a skill following instruction (Baldwin & Ford, 1988). Transfer is further impacted by the external conditions requiring it. Both instructional and transfer outcomes are a function of the two inputs of instructional design and learner characteristics. Instructional design involves the learning principles, the instruction and the delivery method that are selected and combined to create an instructional program.

The characteristics of the learner include the individual differences in cognitive ability, motivation, and personality that influence the effectiveness of an instructional program directly or moderate the relationship between the instructional design characteristics and the outcomes. Baldwin and Ford’s model provides a useful framework for discussing how various factors interact to facilitate learning, retention, and transfer.

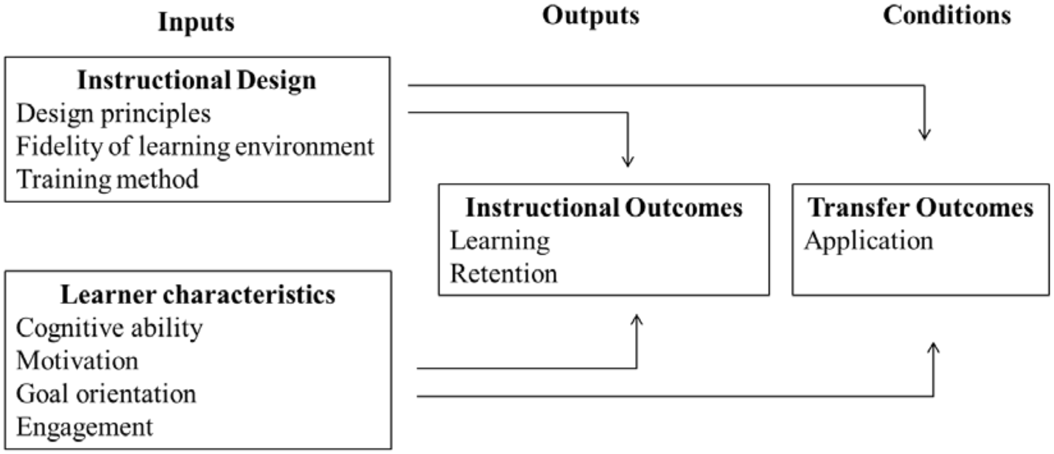


Figure 2.1.Training Transfer Model (adapted from Baldwin & Ford, 1988)

Instructional Design Characteristics

Physical Fidelity

Fidelity, which is the degree to which a virtual or simulated environment corresponds to the real world (Alexander, Brunye, Sidman & Weil 2005), includes numerous subcategories, the most common ones being physical, cognitive, operational and psychological fidelity. Physical fidelity refers to the extent to which simulated and virtual environments physically correspond to the physical environment, while cognitive fidelity is the degree to which the learning environment produces the cognitive responses required in the real world (Hochmitz & Yuviler-Gavish, 2011). Operational fidelity is the extent to which the simulated environment requires the execution of tasks necessary for performance, and psychological fidelity is the extent to which learners perceive similar meanings in the two environments (Baldwin & Ford, 1988). The relative importance of these types of fidelity in any given situation depends on the nature of the task (Stone, 2001). For example, a high level of physical fidelity is of important for technical skills, while psychological fidelity is more important for tasks that require decisions to made under stress.

While previous research has established the efficacy of using both low and high fidelity simulations for instruction, those studies were conducted primarily in such industries as aviation, the military, and healthcare (specifically surgery) where learning in a real-world environment is less viable due to cost, safety, and ethical concerns. As a result, there is limited research comparing outcomes when learning in the physical environment is substituted with learning in a simulated environment for skill-based outcomes (Triona & Klahr, 2003). Further, the majority of the studies investigating learning in 2D and 3D environments has focused on conceptual learning, with few evaluating transfer and none evaluating retention outcomes (Campbell et al., 2002: Finkelstein et al., 2005; Jaakkola, Nurmi, & Veermans, 2011), perhaps explaining why engineering and technical education has been slow to employ online delivery for course and laboratory instruction (Bourne, Harris, & Mayadas, 2005). Further research is need to explore such questions as how and which skillsets can be effectively learned in simulated environments and whether specialized pedagogies need to be developed to support an online technical curriculum including simulated lab experiences (Bernard et al., 2004).

Lab-based instruction. Lab-based instruction is a key educational feature in the science, engineering, and technical disciplines (Jaakkola & Nurmi, 2008) as it provides the opportunity for students to test and apply the theories they have learned during lectures (Auer, Pester, Ursutiu, & Samoila, 2003). During laboratory-based activities, students engage in active learning, conduct experiments, and apply problem-solving skills that facilitate the application of theory in practical situations (Auer et al., 2003; Feisel & Rosa, 2005). This use of physical equipment and materials during instruction represents the highest level of fidelity. In addition, physical laboratories also allow students to experience the sensory characteristics of the equipment and experiments and gain familiarity with the environment in which they will be used (Zacharia, 2007; Zacharia & Olympiou, 2011).

Despite being widely used in science education, researchers have questioned the effectiveness of laboratory instruction (Jaakkola & Nurmi, 2008). Working with physical components and learning through physical manipulation can lead students to develop inaccurate mental models, specifically for complex phenomena, because they can only view processes on the surface without understanding the invisible ones in the system that support theoretical understanding. This weakness in physical instruction represents one of the most commonly acknowledged strengths of simulated instruction.

Simulation-based instruction. Simulated labs, which are being increasingly used effectively in education (Finkelstein et al, 2005; Gillet et al., 2013), allow students to conduct their lab activity online using a simulation, a computer-based representation of a process, system or phenomenon that can be executed and then analyzed (Brey, 2008).

Although a simulation can be developed in a virtual environment, its purpose is to model a process, not physically imitate the system it represents. As a result, simulations and simulated labs can vary significantly in their level of physical fidelity. Such simulations can include 2D, 3D, and virtual laboratories that provide instructional support to students primarily in the science, engineering, medical, and technical fields. Past research has found that these environments can foster attention and engagement in students more readily than some of the more traditional methods (Stone, 2001; Adams, Reid, LeMaster, McKagan, Perkins, Dubson, & Weiman, 2008), suggesting that when simulations incorporate interactivity, animation, and a meaningful context, they can create a “powerful learning environment” (Adams et al., 2008, pg. 418).

One of the primary advantages of simulations is that they can “make the invisible visible” (for example showing the current flow of an electric circuit), helping students learn complex relationships (Finkelstein et al., 2005; Jaakkola, Nurmi, & Veermans, 2011). Simulations also help students to learn in an ideal environment where they can focus on exploring concepts without the complications associated with malfunctioning laboratory equipment (Finkelstein et al., 2005), and they can also provide a safe, more accessible environment in which learners can explore and practice at their own pace (Jaakkola & Nurmi, 2008).

One criticism of simulated labs, however, is that they necessitate students learning in an environment that is fundamentally different from the one in which they may ultimately work (Jaakkola & Nurmi, 208). Furthermore, simulations lack the nuances that exist in the real world and may also oversimplify a complex system. Their ideal representation of a system, while potentially beneficial for learning, may create issues for students when they encounter problems in the real-world environment that they never experienced in the simulation. Additionally, Couture (2004) found that learners may doubt that the principles demonstrated in a simulation are applicable to the real world.

The Effect of Fidelity on Learning Outcomes

Proponents of physical laboratories argue that the use of computer-based interactive simulations limits students from experiencing the hands-on manipulation of real materials, thus distorting reality (Scheckler, 2003). This physicality, which is “the actual and active touch of concrete material,” is believed to be important for learning (Zacharia & Olympiou, 2011, p. 318). Woodfield et al. (2005) also argued that simulations lack the necessary detail and realism to effectively teach proper laboratory technique. However, proponents of computer simulations suggest that it is the active manipulation, rather than the physicality, that is the most important element of laboratory instruction (Resnick, 1998). In addition, Triona and Klahr (2003) suggested that only for perceptual-motor skills are physical practice necessary. For other skills, however, physically manipulating components is not necessary for the information processing and practice needed to acquire them.

Several studies have evaluated using simulated environments in laboratory instruction as a supplement, a substitute, or in some combination with a physical laboratory. For example, Martinez-Jimenez et al. (2003) found that educational software, including virtual laboratories, was a beneficial supplemental tool for helping students prepare for laboratory work, results supported by Dalgarno et al. (2009), who found that a simulated chemistry laboratory could act as an effective tool for helping students become familiar with the laboratory environment prior to attending class. The study conducted by Finkelstein et al. (2005) using Physics Education Technology (PhET) simulations, on the other hand, found that contextually appropriate simulations may be more effective than real lab equipment in terms of educational outcomes. Their study compared students who learned to build circuits using a computer simulation with those who learned to build circuits using physical components, finding that the former on average needed less time to build an electrical circuit than those who had learned in a physical laboratory setting. In addition, they also demonstrated better competence when writing about phenomena associated with electrical circuits.

Campbell et al. (2002) also compared learning outcomes associated with electric circuits in a simulation versus a physical laboratory, finding that a combination of simulation and physical experiences resulted in better performance on a written evaluation than a physical laboratory alone but there were no significant differences in task completion. Other research has also found that students who learned about electricity concepts using a combination of simulation and physical laboratory experiences achieve superior learning outcomes (declarative knowledge gains) compared to those students learning solely in a physical environment or in a simulated environment (Campbell et al., 2002; Zacharia, 2007; Jaakola, Nurmi, & Veermans, 2011).

Though not specifically discussing simulation in relation to physical laboratory instruction, Clark argued that media does not influence learning outcomes as long as the instructional method is controlled (1994); however, several studies comparing learning in simulated and physical environments have not controlled the methods used. For example in Finkelstein's study, students learning about circuits using the PhET simulations were able to learn about current flow as the simulations made the invisible visible but no comparable alternative, such as a video animation, was mentioned as being provided for students learning circuits in the physical condition. As a result, students using the former may have learned more, contributing to the conceptual gains found in this study. The research reported here focuses on the ability of the student to learn the hands-on and technical aspects of the lab activity versus the conceptual benefits that can be provided by 2D and 3D simulations.

Prior research in workforce education has demonstrated that higher levels of fidelity are not necessary, and sometimes even detrimental, to learning and transfer (Alexander et al., 2005). In fact, Alexander et al. (2005) cautioned against the assumption that increasing fidelity will lead to improved outcomes. According to Richards and Taylor (2015), additional studies are needed to compare the educational benefits of 2D versus 3D environments, research that is important because the differences in fidelity between these two represent differences in software maintenance and development costs as well as technological requirements for the system on which the simulation operates. If comparable learning outcomes could be achieved using a 2D simulation, this option may be a better alternative.

However, early research conducted by Regian et al. (1992) concluded that instruction using 2D simulation might be less effective than 3D as translating the representation from the former to the latter may result in additional cognitive load for learners. In some cases 2D representations will be inherently deficient if the data it must imitate are three-dimensional (Richards & Taylor, 2015). Sampaio et al. (2010) suggested that for technical fields like engineering, the use of 3D representations may lead to better learning outcomes than 2D representations. However, while 3D representations provide more flexibility and realism, their increased complexity makes it harder for students to interact with them and can degrade performance (Stuerzlinger & Wingrave, 2011). Novices, in particular, may struggle to grasp all of the information being conveyed in higher levels of fidelity (Gillet et al., 2013). Further, technical issues like poor resolution and lag in the 3D environment can lead to performance deficiencies (Kenyon & Afenya, 1995). As this analysis suggests, additional research is needed to determine what aspects of 2D and 3D representations of tasks are beneficial for learning as well as the contexts and domains best suited for these types of technologies (Richards & Taylor, 2015).

The Impact of Physical Fidelity on Retention Outcomes

There is no extant literature that specifically investigates the effects of the physical fidelity of the learning environment on retention outcomes. However, Ricci et al. (1996) offers insights on the retention in computer-based environments, their study finding that participants who studied a task using a computer game saw more significant improvement between the pretest and the retention assessment than those who used textbooks (Ricci, Salas, & Canon-Bowers, 1996). Of the six attributes the researchers identified as potentially contributing to the effectiveness of games for retention, three – immediate feedback, novelty, and dynamic interaction – could also apply to simulated learning environments.

Farr (1986) and Arthur et al. (1998) also identified different factors and task characteristics that influence retention or, conversely, decay, the loss of knowledge or a skill following a period of nonuse (Arthur, Bennett, Stanush, & McNelly, 1998). The most influential factors for decay are periods of nonuse and overlearning, with this attribute having a positive relationship with degree of nonuse and a negative relationship with degree of overlearning (O'Hara, 1990; Arthur et al., 1998). Decay can be evaluated in terms of the amount and the rate of loss (Farr, 1986), with a typical decay curve demonstrating rapid loss immediately after acquisition and a slowing as the retention period increases until it reaches an asymptote near the pre-instruction level (O'Hara, 1990).

Other factors found to influence decay include the task characteristics and the retention assessment (Arthur et al., 1998). Task characteristics include closed-loop vs open-loop and cognitive vs physical tasks. Closed-loop tasks involve discrete responses and, thus, have a defined beginning and end, while open-loop ones involve continuous responses without a defined beginning or ending. Arthur et al. (1998) found that open-loops tasks were more susceptible to decay, while Farr (1986) found the opposite, that closed-loop tasks were more susceptible. Cognitive tasks require mental operations, and physical tasks require mental exertion and coordination, meaning the latter exhibit less decay than the former (Arthur et al., 1998). Procedural skills, which are particularly susceptible to rapid and expansive loss, decay faster than psychomotor skills (O'Hara, 1990; Ginzburg & Dar-El, 2000). In terms of retention assessment, tasks involving recognition are less susceptible to decay than tasks involving recall. In addition, tasks evaluated behaviorally exhibited less decay than those evaluated cognitively.

The Impact of Physical Fidelity on Transfer

Ricci et al., (1996) suggested that the evaluations completed immediately following instruction alone do not present a clear assessment of learning as measures that include transfer. In addition to learning outcomes, this research seeks to explore how learning in a simulation affects transfer, the ability of students to apply their learning in the real-world. Some researchers support low physical fidelity, suggesting that it helps reduce cognitive load by omitting potentially over-simulating details, meaning students can concentrate solely on what needs to be learned (Zacharia & Olympiou, 2011; Pass & Sweller, 2014). Proponents of high fidelity, however, suggest it supports transfer as the correspondence between the 3D simulation and the real world facilitates recognition, helping to activate the requisite schemas developed using the simulation (Zacharia & Olympiou, 2011).

Few of these studies, however, have evaluated transfer outcomes. Finkelstein et al. (2005) found that students who learned using simulations achieved better transfer outcomes (lower construction times) while Campbell et al. (2002) did not find significant differences in the construction time among those who learned in the physical environment and those who learned in a combined setting (both simulated and physical instruction). More important to the research reported here, both studies evaluated the outcomes using teams rather than individual learners.

Several theories offer insight into how the physical fidelity of the learning environment may impact transfer. Thorndike's identical elements theory posits that there will be a high positive transfer when identical stimulus and response elements are used in the learning and transfer environments (Goldstein & Ford, 2002) because learners are essentially practicing the task which they will have to execute (Yamnill & McLean, 2001). If the stimuli differ, which may be due to the fidelity, but the response is the same, learners may be able to generalize what they have learned and apply it to the transfer environment. This identical elements theory supports utilizing a high level of physical fidelity but only for the tasks or its aspects that need to be transferred. This conclusion is also supported by Farr (1986), who suggested that for relationships among complex abstract phenomena, the physical fidelity of the system only needs to be sufficient to encourage accurate mental representations of the relationships.

According to the general principles theory, transfer is facilitated when students are taught the rules and theories underlying the skills they are learning (Baldwin & Ford, 1988). Simulations, depending on the design of the software, may provide an advantage by helping students to develop a better conceptual understanding of the task under study in addition to fostering more in-depth exploration of a phenomenon (Adams et al., 2008). While the identical elements theory has been regarded as explaining near transfer, the application of learning to similar problems, the general principles theory is more applicable to far transfer, the ability to apply learning to new problems (Yamnill & McLean, 2001).

Cognitive load theory (CLT) also provides relevant insight on how different learning environments can impact transfer, positing that the acquisition of a skill is constrained by an individual's limited information processing resources. Environments or instructional techniques that impose an additional cognitive burden on students, referred to as extraneous cognitive load, are detrimental to learning (Paas & Sweller, 2014). While the effects of this extraneous load may vary based on individual characteristics such as cognitive ability or prior experience, there is currently not enough evidence to suggest whether there is an inherent increase in load due to the physical fidelity of the learning environment. Conversely, environments that increase the germane cognitive load, i. e. those resources devoted to learning, can facilitate skill acquisition and transfer (van Merriënboera, Schuurmanb, de Croock, & Paas, 2002).

Influence of Learner Characteristics on Instructional and Transfer Outcomes

Past research has found that learner characteristics, both dispositional attributes such as cognitive ability and fluid characteristics like level of engagement, have been found to impact the effectiveness of an instructional program and its instructional objectives (Anderson, 1982; Noe, 1986; Snow, 1989). Specifically, learner characteristics have been found to impact learning strategies, effort, and perseverance (De Raad & Schouwenburg, 1996), with more recent research finding that these individual characteristics include cognitive abilities, personality traits, and prior knowledge (Shute & Towle, 2003).

The relationship between the learning environment and learner characteristics on outcomes is referred to as aptitude-treatment interaction (ATIs). Aptitude is a construct explaining the learner’s cognitive ability, prior knowledge and personality traits, and treatment describes the condition or environment that fosters learning (Cronbach & Snow, 1977). With the increasing use of technology in education, there is a renewed interest in ATIs as researchers seek to understand which learner characteristics are most important for designing adaptive learning systems (Shute & Towle, 2003). Currently, the research investigating the interaction of learner characteristics and physical fidelity (e.g., 2D simulation, 3D simulation, or physical labs) on learning, transfer, and retention outcomes is limited. To address this limitation, this study focused on two learner characteristics – cognitive ability and goal orientation. Goal orientation was selected as the personality trait explored here because it has demonstrated positive effects on learning and performance (Kozlowski, Gully, Brown, Salas, Smith & Nason, 2001); similarly, cognitive ability has consistently been found to have a major influence on learning outcomes (Clarke & Voogel, 1985; Kozlowski et al., 2001).

Cognitive Ability

Cognitive ability is an individual’s capacity to perform higher-order mental processes such as critical thinking, problem-solving, and self-monitoring (Clark & Voogel, 1985). Individuals with higher cognitive ability learn and retain more information and are also better able to generalize and apply their knowledge in the real world (Busato, Prins, Elshout, & Hamaker, 2000; Clark & Voogel, 1985). Some research suggests that learners with lower cognitive ability experience more decay for abstract, theoretical concepts than higher ability learners (Farr, 1986), findings suggesting that the latter students should achieve better learning, retention, and transfer outcomes.

In addition, prior research has also suggested that individuals with lower cognitive abilities may need a more structured learning environment while individuals with a higher cognitive ability can perform as well in an less structured one (Snow, 1989). Thus, physical, classroom based-instruction may be more beneficial for learners with lower cognitive ability than the less structured and more autonomous nature of a 2D or 3D simulated environment, particularly when they are used in an online setting. Furthermore, the cognitive load theory suggests that the extraneous cognitive load created by instructional design elements may be detrimental to learning, especially for lower cognitive ability learners who may already have reduced information processing capabilities (Clark & Voogel, 1985; Paas & Sweller, 2014). For example, the increased complexity of the 3D environment may negatively influence an individuals' ability to learn a task an well as negatively impacting transfer as it increases their extraneous cognitive load as well.

Goal Orientation

Goal orientation is used to explain how an individual approaches an achievement task (Elliot & Dweck, 1988). A relatively stable dispositional trait that can be influenced by situational variables, it is commonly conceptualized as performance goal orientation (PGO) and learning or mastery goal orientation (LGO) (Button et al., 1996), with PGO being further subdivided into performance-approach and performance-avoid (Brett & VandeWalle, 1999). The goal orientation of individuals learning a new task or working in an unfamiliar environment influences both their willingness to work through challenges and their performance expectations (Elliott & Dweck, 1988). An orientation towards performance goals can impede the learning of more involved task relationships as these students focus on a narrow set of concepts. As a result, they may perform well initially or during instruction but are unable to generalize or apply the skills in other contexts (Kozlowski et al., 2001). An orientation towards learning goals leads learners to acquire the knowledge and skills required for competency. In addition, it also fosters a desire to explore relationships in greater depth, thus alleviating the fear of making mistakes while building task-specific self-efficacy (Kozlowski et al., 2001). Evaluating how goal orientation affects the ability to learn can provide insights on what type of learning environment, physical, 2D, or 3D, will lead to the best learning outcomes.

Goal orientation has also been linked to skill transfer. According to Stevens and Gist (1997), mastery-oriented learners demonstrated greater skill maintenance in transfer, while more recently Kozlowski et al. (2001) found that although LGO had a stronger correlation in performance ($r = 0.14$ versus $r = 0.098$), both orientations had a similar correlation ($r= 0.243$ versus $r= 0.253$) for performance generalization. As this body of research suggests, individuals with stronger LGOs typically attain better outcomes.

Addressing the Gaps in the Literature Through the Research Aims

As this analysis of the literature suggests, there is a need for additional research identifying how simulated environments of varying levels of physical fidelity influence instructional outcomes; what roles, if any, physicality plays; how learner characteristics influence these relationships; and what happens as learners transition from working in a simulated environment to a physical environment. The research reported here can offer substantive contributions in those areas by addressing its aims of 1) identifying how the physical fidelity of the learning environment impacts instructional (learning and retention) and transfer outcomes, 2) identifying any moderating effects of learner characteristics and 3) identifying how the physical fidelity of the learning environment and the transition from the simulated environment to the physical environment contribute to differences in the learning outcomes achieved by participants. Based on the literature review and the aims of this research, the model seen below in Figure 2.2 was operationalized and applied to the studies reported here.

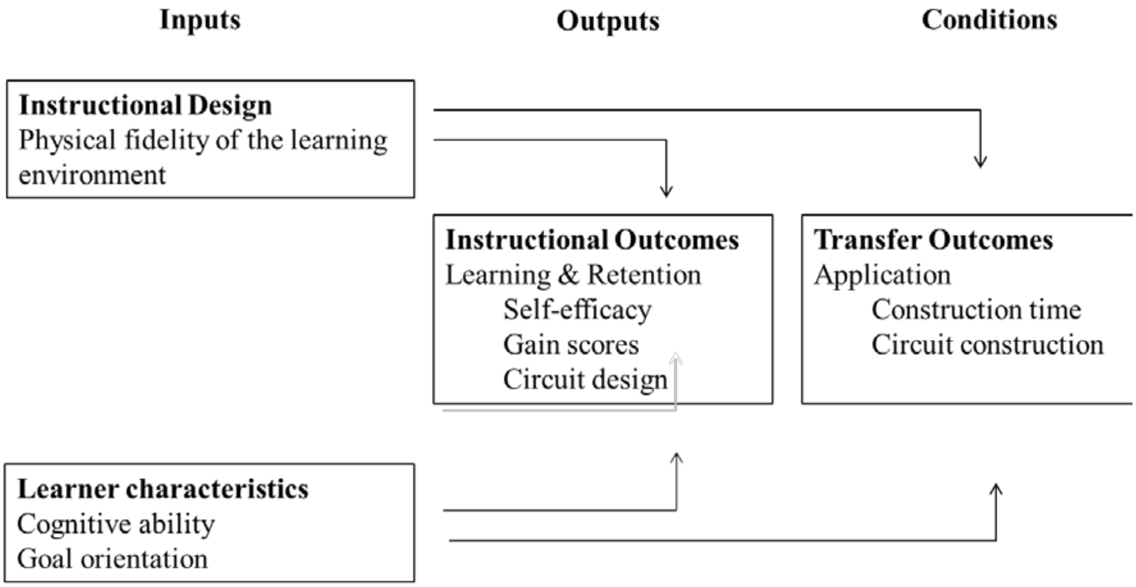


Figure 2.2 Operationalization of Training Transfer model employed for this research (Adapted from Baldwin & Ford, 1988)

Chapter Summary

This literature review, organized using the model of transfer developed by Baldwin and Ford (1988), first covered the extant literature on the impact of physical fidelity on instructional and transfer outcomes. The efficacy of 2D and 3D simulated environments were explored along with several theories of transfer. Next, the chapter examined several important learner characteristics, cognitive ability and goal orientation, that may impact these outcomes and moderate the relationship between physical fidelity and the outcomes. Finally, this review discussed how the three research aims address the gaps in the literature, providing the operationalized model that served as the framework for the research studies presented here.

CHAPTER THREE

DISSERTATION STUDY ONE

Purpose

The purpose of this first study was to address aim one by exploring how individual performance of a task differed depending on the physical fidelity (referred to here simply as fidelity) of the instructional environment and how this relationship was influenced by cognitive ability and goal orientation. Specifically, this study investigated how learning to construct an electrical circuit using a 2D breadboard simulation, a 3D breadboard, or a physical breadboard impacted instructional objectives. These objectives were assessed using affective, cognitive and skill-based outcomes.

Although previous research has identified value in using simulations as a supplement or in combination with laboratory education, little research has specifically investigated the differences in outcomes between 2D and 3D simulations or the influence of learner characteristics (Kim et al., 2013; Richards & Taylor, 2015). The study reported here aimed to explore the role of the fidelity of the learning environment by comparing learning outcomes associated with learning in a 2D, 3D, and a physical environment. This research also aimed to investigate the impact of goal orientation and cognitive ability on learning outcomes for participants learning in those three environments. The work of this chapter was submitted to the *International Journal of Industrial Ergonomics*.

Methods

Participants

Participants for this study included 48 undergraduate and graduate students from a public mid-sized Southeastern University, recruited using word of mouth, flyers, and email blasts. To be eligible, participants could not have been currently enrolled in or have taken a circuits-based class during the previous academic year. Additionally, each participant must have been able to self-report an ACT or SAT score. Of the participants, engineering students represented approximately 33%, while undergraduates accounted for 50% and females comprised 62.5% of the participants. Approximately 79% of the participants reported that they were in the 18-27 year-old category, while the remaining 21% were 28 years old or older. The majority of the participants (92%) reported having little to no prior experience working with circuits. Although 33% of the participants were engineering majors, depending on their specific major and year, they may not have taken a circuits or physics course. This study was approved by Clemson University IRB (# IRB2015-001).

Experimental design

This study utilized a pretest-posttest between subjects design. The fidelity of the learning environment (with three levels, physical, 2D simulation, and 3D) was the between subjects variable. While the primary independent variable (IV) of interest was the fidelity, the covariates included pretest scores, cognitive ability, and goal orientation. The pretest scores were used to control for individual differences in baseline knowledge and any exposure to electrical circuits that was not restricted by the study design. In order to facilitate a holistic evaluation of learning, the dependent measures included affective outcomes, cognitive outcomes, and skill-based outcomes (Kraiger et. al, 1993). The affective measure was self-efficacy (measure using a Likert scale), which is the participant's belief in his/her ability to perform a task (Guthrie & Schwoerer, 1994). The cognitive outcomes were gain scores (posttest score – pretest score) and circuit design (measured as a grade). Gain scores indicate the improvement from the pretest score to the posttest score, and the skill-based outcomes were construction time (minutes) and circuit construction (grade).

Participants' SAT scores were used as a proxy for cognitive abilities. Those who did not take the SAT were allowed to use their composite ACT score. Past research has demonstrated that both the SAT ($r = 0.82$) and the ACT ($r=0.77$) have a strong correlation with cognitive ability (Noftle & Robins, 2007; Koenig, Frey, & Detterman, 2008). A strong correlation ($r=0.87$) has also been demonstrated between composite ACT and total SAT scores (Dorans, 1999). For consistency, ACT composite scores were converted to total SAT scores for the analysis using the conversion chart developed by Dorans (1999). This conversion was used for only six participants. Both learning and performance goal orientations were assessed using an eight- question instrument developed by Button et al. (1996). The reliability of these questionnaires, indexed by Cronbach's alpha, was 0.72 for PGO and 0.78 for LGO. Self-efficacy was measured using a six-question instrument with a reliability of $\alpha = .82$ (Guthrie & Schwoerer, 1994). All questions used five-point Likert scales anchored by strongly disagree and strongly agree.

Procedures

After completing the consent form, participants completed a 5-question multiple choice, paper-based pretest examining their knowledge of basic electrical concepts (Appendix A). The pretest included questions on defining electrical concepts (e.g., voltage, resistance, and current), identifying circuit diagram symbols (e.g., switches, resistors, battery, and LEDs), designing a circuit diagram, demonstrating an understanding of breadboard functionality, and applying Ohm’s law. Each question had four answer options. Next, they completed a demographic survey, where they reported their SAT/ACT score, and the goal orientation instruments (Appendices B and C). Students subsequently watched a 28-minute video lecture on circuit analysis and basic circuit construction. This video included three sections, each with individual learning objectives and practice exercises.

Following this instruction, students watched two videos demonstrating how to construct a circuit. The construction video participants watched depended on the condition to which they were randomly assigned. That is, participants in the physical condition watched a video of a researcher using the physical components, and similar demonstrations were used for the 2D and 3D conditions involving their respective technology. Participants in the physical condition practiced constructing circuits using an 800-point solderless breadboard (Figure 3.1), while participants in the 2D condition practiced using a 2D breadboard simulation (123D Circuits Arduino 2D Breadboard) (Figure 3.2) and participants in the 3D condition practiced using a 3D breadboard (National Instrument Multisim Educational Edition Version 13) (Figure 3.3).

During these videos, participants were shown how to use Ohm’s law to calculate the resistor values needed for their circuit, how to design their circuit diagram and how to construct their circuit. Because students in the 2D and 3D conditions also had to learn to use the software, the instructional videos for each of the conditions varied in length. In total, they ranged from 7 to 17 minutes. The study set-up included a computer workstation with two monitors so that participants could watch the video on one screen while constructing their practice circuits on the second. Participants navigated the 2D simulation and 3D environments using a mouse and keyboard. Students in all conditions used comparable circuit components – LEDs, switch, resistors, and batteries - and had access to the instructional videos during their practice sessions.

Participants were given three practice activities to complete. One of these practice activities instructed participants to complete a series circuit using a three-prong switch, while the second had participants construct a parallel circuit and the last activity demonstrated how to construct a parallel circuit with the switch at one connection. During these practice sessions, they were provided with feedback concerning the accuracy of their calculations and the construction of the circuit and were referred to the appropriate video for review for any errors they made. The participants were not allowed to continue the experiment until they had successfully completed the practice activities. Although this requirement led to varying practice times, it was essential that participants demonstrated a minimum level of proficiency before continuing.

Following these practice sessions, the participants completed a post-survey assessing their self-efficacy and a 5-question multiple choice, paper-based posttest

(Appendices D and E). The posttest was of the same structure and length, and used the same types of questions as the pretest. Finally, the participants from all conditions constructed a simple circuit including a switch and 3 LEDs on a physical breadboard without access to the video lectures (Appendix F). Students had to first design the circuit and use Ohm’s law to determine the correct amount of resistance needed based on the voltage source they selected (a 9 volt battery or a 1.5 volt AA battery) The circuit needed to be constructed such that the two LEDs were connected in series and powered by a switch and the third LED was connected in parallel. While completing this construction task, they were video recorded using a GoPro Hero4 Black camera positioned above them to record an aerial view of their work surface without being intrusive.

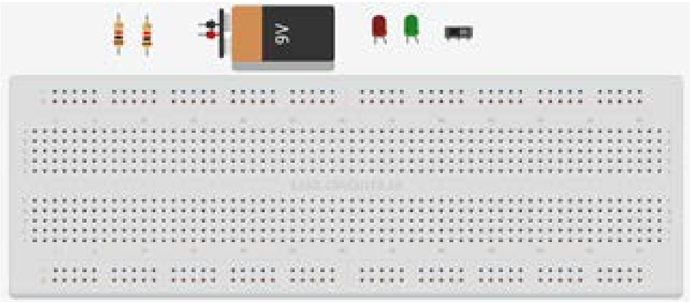


Figure 3.1. A screen shot of the Arduino 2D Breadboard (123d.circuits.io)

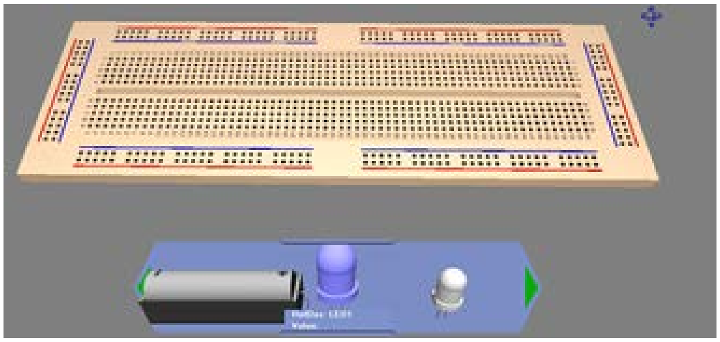


Figure 3.2. A screen shot of the NI Multisim Breadboard (http://www.ni.com/multisim/)

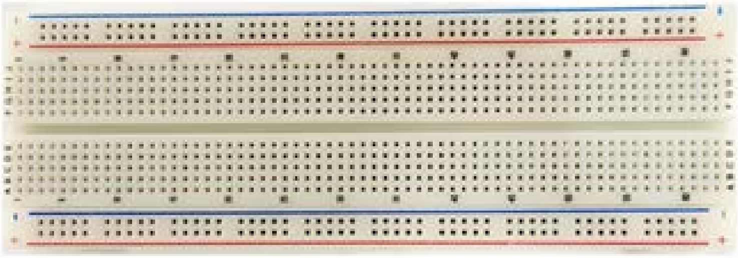


Figure 3.3. 800 Point Solderless Breadboard

Results

Analysis

The data were analyzed using SPSS 22, and ANOVAs were used to analyze the effects of the predictor variables on self-efficacy, gain scores, and construction time. In addition, an ordered logistic regression was used to analyze the effects of the predictor variables on circuit design grade and circuit construction grade. The circuit design and circuit construction were graded for accuracy on a three-level scale, no errors (correct), minor errors, and major errors. All of the models were evaluated at the alpha = .05 level. Prior to analysis, the data were evaluated to ensure they met the assumptions – independence, normality, and homogeneity of variance – needed for an ANOVA as well as the assumptions, including proportional odds, of an ordered logistic regression. These assumptions were met, and, therefore, the analysis methods were deemed appropriate. While this study involved 48 total participants, the data for one participant, who was in the physical condition, were removed because he failed to report his SAT or ACT score as required by the study. Furthermore, three additional participants withdrew from the study, resulting in a different sample size for the circuit design and the construction activities. The total number of participants in each condition for all dependent measures was 15 in the physical condition, 16 in the 2D condition, and 13 in the 3D condition.

Results

Participants were given a pretest to assess their knowledge of circuit theory and construction. A one-way ANOVA found no significant differences, *F*(2,44) =.123, p = .884, in the pretest scores of participants in the three conditions, suggesting no detectable differences in their pre-existing knowledge.

The first research question focused on the impact of the fidelity of the learning environment on affective, learning, and skill-based learning outcomes. The first dependent variable assessed was self-efficacy, an affective outcome. The predictor variables included in this model were fidelity, LGO, and PGO. Four participants did not complete the self-efficacy survey, resulting in a total of 43 observations analyzed. Based on the ANOVA results, fidelity (*F*(2,39)=3.809 (p=.031)), was a significant predictor (Table 3.1). The mean self-efficacy was 4.36 (SD= .58) for participants in the physical condition, 3.76 (SD=.67) for participants in the 2D condition, and 3.93 (SD=.75) for participants in the 3D condition (Figure 3.4). Subsequent post hoc analysis completed using the least significant differences (LSD) test revealed significant differences in self-efficacy between participants in the physical condition and participants in the 2D condition, (p=.014), and between participants in the physical condition and the 3D condition, (p=.038). LGO and PGO were not significant predictors of self-efficacy. Fidelity had a unique effect size of sr^2 = .378.

Learning outcomes were assessed using gain scores and circuit design. The average gain score for all conditions was 0.24 (SD = .21), based on a maximum score of one. The pretest scores ranged from 0.10 to 0.80, and the posttest scores ranged from 0.45 to 1.00. This model included the predictor variables of LGO, PGO, cognitive ability, and pretest scores. Based on ANOVA results, LGO (*F*(1,40) = 5.02 (p = .031)), cognitive ability (*F*(1,40) =6.49 (p=.015)), and pretest scores (*F*(1,40) = 31.09 (p<.001)) were significant predictors of gain score. Pretest scores had the highest unique effect size (sr^2 = .378). Cognitive ability and LGO had unique effect sizes of sr^2 = 0.06 and sr^2= 0.057, respectively. Fidelity and PGO were not significant predictors of gain score (Table 3.2).

Table 3.1. ANOVA for participants' self-efficacy following instruction and practice

	Sum of Squares	df	Mean Square	F	P-value
Fidelity	**3.16**	**2**	**1.58**	**3.81**	**0.031**
PGO	1.35	1	1.35	3.26	0.079
LGO	0.666	1	0.666	1.61	0.212
Error	16.16	39	0.414		
Total	21.2	43			

R Squared = 0.237 (Adjusted R Squared = 0.159)

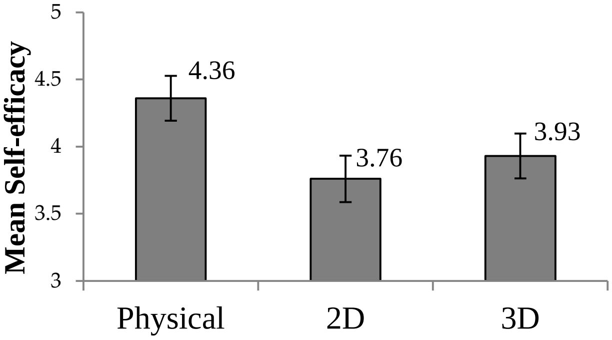


Figure 3.4. Mean SE with standard errors for each condition

Table 3.2. ANOVA for participants' gain score from the pretest to the posttest

	Sum of Squares	df	Mean Square	F	P-value
Fidelity	0.07	2	0.034	1.52	0.232
LGO	**0.11**	**1**	**0.113**	**4.86**	**0.031**
PGO	0.00	1	0.005	0.23	0.886
Cognitive ability	**0.15**	**1**	**0.118**	**5.10**	**0.015**
Pretest score	**0.70**	**1**	**0.741**	**32.0**	**<0.001**
Error	0.90	40	0.023		
Total	1.98	46			
R Squared = 0.544 (Adjusted R Squared = 0.476)					

Circuit design was graded on a scale ranging from major errors to no errors (Table 3.3). Major errors included such mistakes as designing a series circuit instead of a parallel circuit, while minor errors included using incorrect symbols. As one participant completed the diagram prior to withdrawing from the study, there were a total of 45 observations for this model. The majority of participants (51%) were able to correctly design the circuit (Table 3.3). An ordered logistic regression was used to analyze the effects of fidelity, cognitive ability, LGO and PGO on circuit design grades (no errors, minor errors, and major errors). The test of parallel lines for the ordered logistic model was found to be insignificant, suggesting the proportional odds assumption was met (p=0.161).

Table 3.3. Frequency of errors in participants' circuit design task

Condition	**No errors**	**Minor Errors**	**Major Errors**	**Total**
Physical	9	5	1	15
2D	7	6	3	16
3D	7	5	2	14
Total	23	16	6	45

To make the interpretation of the results more meaningful, the continuous variables were dichotomized into high and low values based on a median split. For circuit design, only cognitive ability was found to be a significant predictor, $\chi 2$ (1, N=45) = 5.51 (p=0.019). The odds of designing the circuit correctly were 4.57 times higher [95% CI: 1.32, 17.15] for participants with high cognitive ability compared to participants with low cognitive ability. Fidelity, PGO, and LGO were not significant predictors.

Skill- based outcomes were measured using the total construction time and circuit construction grade. As mentioned earlier, three participants withdrew from the experiment prior to completing the construction activity, resulting in 44 observations. Construction time began once participants received the directions and ended when participants submitted their final circuits. The predictor variables included in this model were fidelity, goal orientation, and cognitive ability. Fidelity was a significant predictor of construction time, $F(2,33) = 4.87$ (p =0.014) (see Table 3.4). The mean construction time differed among conditions, with participants in the physical condition taking 15.47 minutes (SD=12.39), participants in the 2D simulation condition taking 29.88 minutes (SD=14.76), and participants in the 3D condition taking 30.43 minutes (SD=16.91). Subsequent post hoc analysis using LSD found significant differences between the physical condition and the 2D condition (p=0.018) as well as between the physical condition and the 3D condition (p=0.019). However, there were no significant differences in mean construction times between the 2D and 3D conditions (p=0.620). The effect size for fidelity was $sr^2 = 0.19$. LGO, PGO, and cognitive ability was not a significant predictor of construction time. However, LGO was found to moderate the relationship between fidelity and construction time. The unique effect size for this moderating variable was $sr^2 = 0.134$

Circuit construction grades, like the circuit design grades, were scored on a scale ranging from major errors to no errors (Table 3.5). For the construction activity, all participants constructed their circuits using the physical breadboard. With respect to circuit construction grades, major errors included mistakes such as the inability to close the circuit properly, while minor errors included incorrect placement of the switch. Of the 44 participants who attempted construction, 52% were able to correctly construct the circuit. An ordered logistic regression was used to analyze the effects of all the IVs – fidelity, cognitive ability, LGO and PGO – as well as the circuit design grades on circuit construction. Similar to circuit design, the continuous variables in the analysis were dichotomized using median splits to facilitate interpretation. The proportional odds assumption for this model was also met as the test of parallel lines was found to be insignificant (p=0.77).

Table 3.4. ANOVA for participants' construction time on the physical breadboard

	Sum of Squares	Df	Mean Square	F	P-value
PGO	12.35	1	12.35	0.056	0.815
LGO	1.06	1	1.06	0.005	0.945
Cognitive ability	254.46	1	254.46	1.15	0.292
Fidelity	**2161.65**	**2**	**1080.83**	**4.87**	**0.014**
Fidelity*Cognitive ability	103.67	2	51.84	0.233	0.793
Fidelity*LGO	**1513.34**	**2**	**756.67**	**3.41**	**0.045**
Fidelity*PGO	322.13	2	161.07	0.725	0.492
Error	7328.61	33	222.08		
Total	11288.31	44			
R Squared = .351 (Adjusted R Squared = .134)					

For circuit construction, circuit design ($\chi2$ (1, N=44) = 5.32, p=0.024) and fidelity ($\chi2$ (2, N=44) = 2.93, p=0.021) were found to be significant predictors. The odds of constructing the circuit correctly were 0.04 times [95% CI: 0.003, 0.617] lower for participants who made major errors in their circuit designs than for participants who made no errors. In addition, the odds for participants in the 3D condition were 0.064 times lower [95% CI: 0.003, 0.617] than the odds for participants in the physical condition.

Table 3.5. Frequency of Errors in Participants' Circuit Construction Grades

Condition	**No errors**	**Minor errors**	**Major Errors**	**Total**
Physical	11	2	2	15
2D	8	2	6	16
3D	4	2	7	13
Total	23	6	15	44

The second research question focused on the moderation effects of learner characteristics on the relationship between fidelity and the learning outcomes. As previously mentioned, there was a moderation effect of learning goal orientation on the fidelity for construction time, *F*(2, 33) = 3.41 (p=0.045) (Table 3.4). In the 3D condition, participants who had a higher than average LGO constructed their circuits faster (24.11 minutes, SD=9.61) than those with a lower than average LGO (41.8 minutes, SD =22.21). In the 2D condition, participants with a higher than average LGO took longer to construct their circuits (33.86 minutes, SD = 17.32) than participants with a lower than average LGO (26.78 minutes, SD = 12.61) (Figure 3.5). In the physical condition, participants with a higher than average LGO also constructed their circuits more slowly (18.22 minutes, SD = 15.24) than those with a lower than average LGO (11.43 minutes, SD 4.89). Further analysis found that this pattern was consistent even after removing the participants who gave up or were ultimately unsuccessful in their construction attempt.

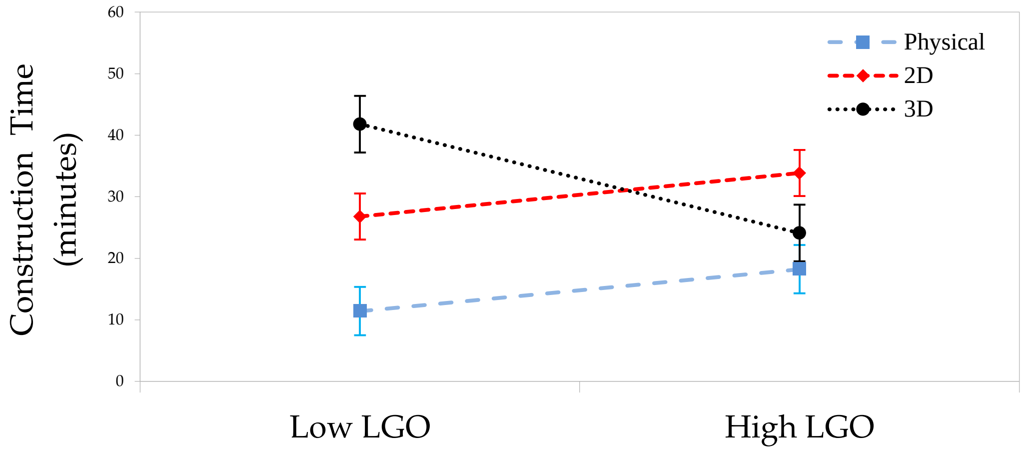


Figure 3.5. Interaction between LGO and Physical Fidelity on Construction Time

Discussion

The aim of this study was to investigate how learning in different levels of fidelity influenced affective, cognitive, and skill-based learning outcomes. This breakdown of learning outcomes is distinct from the existing literature evaluating the impact of simulated learning environment in that the results of these previous studies have focused predominantly on cognitive outcomes using gain or posttest scores **(**Zacharia, 2007; Jaakola & Nurmi, 2008; Jaakola, Nurmi, & Veermans, 2011**).** The results of this study demonstrated that the fidelity of the learning environment did impact the affective and skill-based learning outcomes but not the cognitive outcomes (i.e., gain scores and circuit design grades). Participants in the physical condition had higher self-efficacy, constructed the circuit faster and had higher odds of successful construction than participants in both the 2D and 3D conditions. However, fidelity was not a significant predictor of cognitive outcomes – gain score and circuit design. With, the exception of self-efficacy, which has not been previously studied, these findings were consistent with previous research.

There is no literature that specifically evaluates the impact of fidelity on self-efficacy; however, previous research has suggested that self-efficacy may be influenced by instructional interventions (Zimmerman, 2000). Fidelity exhibited a sizable unique effect size on participants' self-efficacy. Participants in the physical condition had a higher self-efficacy than the participants in both the 2D and 3D conditions. While individuals in the physical condition had the advantage of fidelity for the circuit construction task as it was completed on a physical breadboard, the participants did not know this beforehand. Because participants recognized that constructing a circuit is a hands-on task, it is possible that those in the 2D and 3D conditions realized that what they learned would inherently be different from how the task would be performed in the real world and, as a result, had a lower self-efficacy. This lower self-efficacy potentially impacted participants' effort and persistence on the circuit design and construction task (Zimmerman, 2000). Additionally, participants with lower self-efficacy are more susceptible to adverse emotional reactions if they encounter challenges (Zimmerman, 2000).

Fidelity was also a significant predictor of construction time and circuit construction. Participants in the physical condition were able to construct the circuit twice as fast as participants in either the 2D or 3D condition and were more likely to construct the circuit correctly. While many studies have investigated conceptual gains associated with learning in 2D and 3D environments, few have looked at skill-based outcomes. Campbell et al., (2002) found no significant differences in the ability of students to complete the laboratory assignment between participants learning under different levels of fidelity. Finkelstein et al., (2005) found that participants who had learned to construct circuits in a 2D simulation were able to complete their laboratory assignment faster than those who learned using physical components. One major difference between the present study and the two prior studies is that participants in those studies worked in teams whereas participants in this study worked individually. Additionally, participants in the prior studies had to complete a full laboratory assignment, including a construction task and report, whereas participants in this study just completed a circuit construction task as a measure of skill-based outcomes.

The identical elements theory may explain this difference in construction time between participants in the three conditions as it posits that there will be a higher positive transfer when the instruction environment is identical to the performance environment (Goldstein & Ford, 2002). Participants who practiced in the physical condition had the benefit of a higher level of fidelity, a situation which likely contributed to their ability to construct the circuit much faster than participants in the other two conditions. Participants in the 2D and 3D conditions likely needed additional time to acclimate to working with physical components. Additionally, some tasks that participants had to perform in the physical environment were not required in the 2D and 3D environments. For example, in the simulated environments, participants did not have to read resistors bands to identify the resister’s resistance but were able to input the resistance values needed for a specific resistor. Although students were shown how to read resistors during the video lecture, those in the 2D and 3D environments did not receive additional practice with that aspect of the task. As a result, some participants transitioning from the simulated environments may have struggled reading the resistors and this contributed to a higher construction time.

Results showed that fidelity did not significantly predict gain scores or circuit design grades. This finding is in line with prior research that has found that are no differences in cognitive outcomes between physical and simulated environments when the instructional method is controlled (Jaakola & Nurmi, 2008; Triona & Klahr, 2003; Zacharia & Olympiou, 2011). Clark (1994) has also previously suggested media will not influence learning outcomes if the instructional method were identical. However, improvements in cognitive outcomes have been found when learning in a combined simulated environment and a physical environment (Campbell et al., 2002; Zacharia, 2007; Jaakola, Nurmi, & Veermans, 2011).

There were few differences detected in the learning outcomes between the 2D simulation and the 3D simulation. There were no significant differences in self-efficacy and construction time for participants in the 2D and 3D conditions. However, participants in the 2D condition did have higher odds of constructing the circuit correctly than those in the 3D condition. This suggests that the 2D condition may be the better alternative. Existing literature has found that increasing the level of fidelity does not necessarily improve learning outcomes (Alexander et al., 2005). Higher levels of fidelity may present too much information, particularly for novices, and this may increase cognitive load (Gillet et al., 2013; Paas & Sweller, 2014). Additionally, the increased complexity of operating in a 3D environment can make it more difficult for students to learn in the environment and this can also result in poorer performance (Stuerzlinger & Wingrave, 2011).

A second aim of the study was to investigate the effect of learner characteristics on learning outcome as well as any moderating effects of learner characteristics on the relationship between fidelity and learning outcomes. Unlike fidelity, learner characteristics did impact the cognitive outcomes - gain scores and circuit design. These findings were consistent with prior research. LGO was a significant predictor of gain score. Research also suggests that individuals with higher LGOs perform better as they devote more effort in developing an understanding of the content so those with a higher LGO were also expected to achieve higher gains (Button et al., 1996). Cognitive ability was a significant predictor of both gain score and circuit design. This was anticipated as higher cognitive ability is associated with increased learning, retention and de-contextualization of learning (Clark & Voogel, 1985). Specifically for circuit design, while most participants knew how to construct a diagram, those with a higher cognitive ability were better able to design a circuit that was different than what had been designed during practice.

The study also found that the effect of fidelity on construction time was moderated by LGO. For participants in the 3D condition, having a high LGO resulted in a lower construction time. However, for participants in the 2D and physical condition, having a higher LGO resulted in a higher mean construction time. Currently there is no existing literature, the researcher is aware of, on how goal orientation interacts with fidelity to influence learning outcomes. Participants with higher than average LGO in the

2D and physical conditions were perhaps more meticulous and as a result, spent more time ensuring their circuit was constructed correctly. These participants may have also been more willing to explore during the construction process. One possible explanation why participants in the 3D condition did not exhibit the same pattern related to construction time concerns a specific feature of the 3D software. The 3D software provided participants with feedback about their connections when they were constructing their circuit; participants with a low LGO may have depended more heavily on this feedback than those with a high LGO and as a result took longer to construct their circuit with the physical components. Prior research has found that providing a high level of feedback during instruction can hinder independent performance (Goodman & Wood, 2004).

Limitations

There are several limitations associated with this study. First, the sample size was relatively low (16 per condition) and was reduced further due to the withdrawal of several participants. As a result, the power of the analysis was not ideal. Although both undergraduate and graduate students were used to create a more diverse group of participants, a more representative sample would have included non-traditional students and students in associate's and certification programs. Non-traditional students are more likely to enroll in online courses than traditional students (Allen & Seaman, 2007) and represent a prime target for computer-based hands-on laboratories. Furthermore, there were characteristics of the software design, rather than an innate characteristic of 2D simulations and 3D learning environments, that may have been detrimental to participants' performance when they transitioned from the simulated environment to the physical environment. For example, both the 2D and 3D software allowed participants to type in the resistance value needed for the circuit. Although using a resistor color code sheet was introduced in the video lecture and participants were shown a demonstration of how to read the resistor color codes, participants in the 2D and 3D conditions did not have to practice selecting a resistor using a resistor color code sheet. This potentially made it more difficult for them when they transitioned to working on the physical breadboard. These issues do, however, provide insights regarding how the design of simulated environments can be improved to support learning and transfer. The software packages used in this study were off the shelf and thus there were differences between the 2D and 3D environments that could not be resolved. The major difference was that the 3D environment used a dual view with a circuit schematic and the breadboard that provided participants with feedback concerning which circuit components were connected correctly. There may have also been small differences in how a user would interact with the system in the 2D and 3D environments. Lastly, constructing a circuit is a very specific task that few students are required to perform as part of a course or on the job. Even the majority of the participants who were engineering majors, many of whom are required to complete a survey circuits course, expressed doubt in their ability to work with circuits. While this task was chosen, in part, to build on the findings of previous research, this limits the generalizability of the results. While it may be compared to other cognitive procedural tasks, future research should evaluate the extent to which the results from this study are generalizable across tasks and other types of laboratory-based instruction.

Conclusions

This study found that fidelity impacted the affective and skill-based learning outcomes for participants learning to construct a circuit on a breadboard. Individuals who learned to construct a circuit using a physical breadboard had higher self-efficacy and performed better on skill-based learning outcomes than individuals who learned in the 2D or 3D conditions. While these findings suggest that instruction using physical components was superior, there is evidence of transfer for those who learned to construct a circuit in a simulated environment. Of the 29 participants in the simulated conditions who attempted construction, 12 were able to effectively transition into the physical workspace despite needing to identify differences between the two environments and adjust their processes based on these differences. Some acclimation to the physical environment will be necessary; enhancements in both the 2D and 3D software could help address some of the issues participants faced when they transitioned.

Simulated laboratories do have some practical benefits over physical laboratories. Simulated laboratories can be offered in an online setting and do not require the equipment and facilities needed for physical laboratories. The maintenance costs for these environments may also be lower than physical laboratories. Learners have increased access as instructors and/or teaching assistants do not need to be present. Safety can be a major concern as well as cost, two factors which may limit the students' ability to experiment and explore using the physical tools and equipment. This study also found that the 3D condition offered no significant advantages over a 2D simulation for teaching students how to construct a circuit on a breadboard. Participants in these two conditions were comparable in terms of affective (self-efficacy) and skill-based outcomes (construction time). However, participants in the 2D environment had higher odds of constructing their circuit correctly than those using the 3D. Therefore, it may not be necessary to devote the time and resources to develop, implement, and maintain 3D environments when comparable results can be achieved in 2D environments.

While the fidelity of the learning environment influenced the affective and skill-based outcomes, learner characteristics impacted the cognitive-based outcomes. An interaction effect was also found between fidelity and LGO for construction time. These results suggest that identifying and evaluating learner characteristics may help achieve better results when selecting the learning environment. However, there are additional learner characteristics, such as spatial ability, that may also influence performance when using different levels of fidelity. Future research should continue to identify which learner characteristics are most important and how they impact various learning outcomes.

Identifying whether more technical and hands-on tasks can be effectively learned in simulated environments is an important question for expanding course offerings in online education and subsequently increasing access and educational equity. Online education has been highly effective in increasing educational opportunities for students, particularly nontraditional students (such as those who are older, attend school part-time, or are financially independent) (Allen & Seaman, 2007). However, at the postsecondary level, many of the online courses offered by traditional universities focus primarily on conceptual learning (e.g., business, education, and health programs) (Allen & Seaman, 2006). Non-traditional students wanting a technical degree may be constrained to course offerings at their nearest educational institution because few institutions currently offer technical curricula in online settings. The results of this study provide insights about whether, and potentially how, hands-on tasks can be effectively taught in online laboratory settings.

Chapter Summary

This chapter addressed the first aim of this research by identifying how the physical fidelity of the instructional environment impacted learning outcomes for participants learning to construct a circuit on a breadboard. This study also investigated how that relationship was influenced by cognitive ability and goal orientation. Although there was evidence of transfer, participants learning in the physical condition, on average, made fewer errors in the circuit design and construction, and constructed the circuit faster than participants in the 2D and 3D conditions. Participants in the physical condition also reported a higher self-efficacy than participants in the simulated conditions. These findings, however, provide little insight about what specific characteristics of the simulated and physical environments influenced these outcomes (affective and skill-based). In the next study, semi-structured interviews were conducted with a subset of the participants from this first study to understand how the fidelity of the learning environment influenced their perceived proficiency and transition during the construction task.

CHAPTER FOUR

DISSERTATION STUDY TWO

Purpose

This study explored how the physical fidelity of the learning environment and the transition from the simulated to the physical environment contributed to differences in the outcomes achieved by the participants. This study addressed the second aim of the research conducted for this dissertation. The work reported in this chapter was published in the 2016 Conference Proceedings of the American Society for Engineering Education (Alfred, Morris, Neyens, Gramopadhye, 2016).

Methods

Participants

This study, approved by the Institutional Review Board of Clemson University (IRB # 2015-001), used a purposeful sample of 20 participants who had participated in the original study (Table 4.1). The participants were selected to ensure that the study included:

- Representatives of those in the physical, 2D, and 3D conditions
- Undergraduates and graduate students
- Males and females
- Students of color and white students
- Engineering and non-engineering majors
- Successful and unsuccessful in completing the construction task

Table 4.1. Representative Sample of Participants

Level of physical fidelity			**Class**	**Gender**	**Race**	**Major**	**Construction**
Physical	2D	3D	Grad	F	Students of Color	Engineering	Successful
6 (30%)	8 (40%)	6 (30%)	13 (65%)	10 (50%)	12 (60%)	7 (35%)	12 (60%)

Procedures

Once participants signed the consent form, they were given a short overview explaining the purpose of the study. They were then informed of its structure and were provided with an opportunity to ask questions. After this brief summary, a semi-structured interview was conducted with each of the participants on their understanding of the circuit construction task, their process for constructing the circuit, and their troubleshooting strategy. The participants were also asked about their emotional state during the study as well as their motivation for taking part in it. This interview was audio recorded and then transcribed by a transcription service blind to the objectives of the study. Each transcript was verified, and any mistakes or inconsistencies in the transcription were corrected by the research team.

Following each interview, the researcher wrote memos about some of the key ideas from the interview as outlined by the qualitative research process (Strauss & Corbin, 1990). After several interviews the researcher revisited the notes from the individual interviews and then compared the notes to identify trends (Rubin & Rubin, 1995). This process was repeated with every four sets of interviews and again at the end of the interview process. In the research memos, the lead researcher also reflected on these interpretations, noting her own thoughts, feelings, and preconceptions about the phenomena being studied.

After all 20 interviews were completed, the researcher defined an initial set of concepts using the memos as well as the transcriptions. Thoughts, quotes and paraphrased excerpts from the various interviews were grouped based on similarity using an affinity diagram. These groups of concepts were then used to define categories to represent higher level abstract concepts that are similar in nature but can be contrasted based their properties (Strauss & Corbin, 1990).

The categories generated from this process were then used to code the transcriptions using Dedoose, a qualitative and mixed methods research software. Sentence fragments, sentences, and entire sections of interview data were coded based on the main idea being conveyed by the participant. This open coding process was completed by two members of the research team. Following individual coding, the two coders reviewed several of the coded transcriptions to compare results. Interrater agreement was not calculated as the coders sought consensus on the codes selected for each transcribed interview. The research team then identified the properties and dimensions of the categories. Properties that were redundant or could not be analyzed across dimensions were eliminated. Finally, themes were developed from the data based on similarities in the categories as well as their properties.

Results

Analysis

The initial concepts were derived from both participant quotes and the researcher’s memos by focusing on key aspects of the interviews, the memos written for each, and the trends identified from revisiting these memos. Below is an example of a direct quote from a participant discussing his affect after successfully constructing the circuit. The bolded statement in the bracket represents the concepts identified.

> “When it finally ... like we had a part where it lit up, something had to light up. And it felt good when it lit up **[“joy”]**, you know, like, "I did it. I kilt it." In my head, you know? Like, "I'm the best at this. **[“confidence”]**

Here is another statement from a participant describing how her learning style helped shaped her approach to the circuit construction task.

> “I mean I'm a much more sort of like, visual conceptual thinker and learner [“**learning style”**]. So it always helps me if I have a pen and I draw either where I'm, where I think I'm at or where I want to go. So, sometimes I would draw like, you know um, if we learned, here's how you set up a ser- a simple series circuit. I might draw that before like, I started **[“strategy”]**. So then I could be like, "Okay, if it's a series, and I need like, three bolts, then I need to put like, a thing here, a thing here and a thing here."

The researcher’s memos also provided a source of data as it summarized some of the major points of an interview as shown in the examples below.

> Spoke about the simplicity of working in the 3D environment **[“simplicity”].** Performing well in the 3D environment and struggling in the physical environment led him to believe “there’s something wrong with the breadboard” **[“attribution”].** Also discussed a downward slope of confidence **[“confidence”].** Better understanding of circuit concepts then most participants [“**circuit knowledge”**]. Well in-tuned with differences between 2D simulation and physical environment. Mentioned the need for “mental rotation” because orientation of breadboard in 2D simulation differed from orientation of breadboard in training

[“**differences in learning environment”**]. Prior experience with circuits shaped view of 2D simulation [“**past experience”**].

Once these concepts were identified, they were grouped based on similarity. For example, participants’ discussion of their confidence, anxiety or frustration was placed into a one group. Participants’ discussion of their major, learning preference or personality was placed into another group.

The groupings were then analyzed to determine a broad category that best fit all of the concepts in the group. In the first example listed above, confidence, anxiety, and frustration were categorized under affect. In the second example, major, learning preference, and personality were categorized as self-descriptions. After developing and revising the categories, a final list of nine categories were selected to code the interviews and are shown in Table 4.2.

The 20 interviews were then coded individually by two members of the research team using Dedoose. Once all interviews were coded, the properties and dimensions of the categories were defined. Properties describe the general characteristics of a category, while dimensions describe the location of the property along a range or continuum (Strauss & Corbin, 1990). For two categories, motivation and emotional state, the researchers used well-defined properties from the extant literature. Motivation was analyzed base on the orientation – extrinsic to intrinsic – and level – low to high (Ryan & Deci, 2000). Emotional state was evaluated in terms of valence – negative to positive – and arousal – low to high (Kensinger, 2004). The researchers defined the properties and dimensions for the remaining seven categories as shown in Table 4.3.

The research team then began searching for the trends among the categories and the properties within them that were most influenced by the physical fidelity of the learning environment. Some of the categories, such as past experience with circuits and general circuit knowledge, although varying widely among participants, appeared unrelated to the physical fidelity as the students described prior courses and informal settings where they learned about circuits at various levels of breadth and depth. Motivation was less varied but was also unrelated to the different levels of fidelity, with participants discussing their relationship with the researcher, general interests in research, financial incentives, and "research karma," which is participating in the research studies of others so that others will participant in your own research study, as their reasons for participating. For the self-description category, participants tended to relate their major, their learning preference and/or their personality to their performance. Some also used these descriptions to explain their preferences for one learning environment (such as the physical) over the other (such at the 2D or 3D environments).

The categories most affected by physical fidelity were the ones that described characteristics of the learning environment, attributions, affect, strategies and tactics, with the first three having the highest level of co-occurrence. Strategies and tactics, while not having a high level of co-occurrence, were the categories that were difficult for the coders to distinguish. Based on reviewing these categories, their properties and their dimensions as well as their relationship, the researchers identified three primary themes of support, physical transition, and emotional transition for explaining how the physical fidelity of the learning environments impacted performance.

Table 4.2. High Level Categories Generated from Memos and Transcripts

Category	Description	Example concepts
Past experience with circuits	Past experience working with or learning about circuits	Electrical engineering course, physics lab, circuits kit
General circuit knowledge	General description of concepts related to circuit construction and analysis	Ohm's law, parallel circuit, series circuit, forward voltage
Characteristics of the learning environment	Attributes of the physical, 2D or 3D environments that participants like/dislike or influenced their performance in any way	Simplicity, feedback, exploration
Attributions	Description of a reason for their struggles and successes during the construction task	Self, training, environment, equipment
Self-descriptions	Description of personality, field of study, learning style, physical characteristics, interests etc.	Major/program, career field, learning style, personality
Affect	Description of a particular emotion experienced during the study	Confidence, frustration, joy, anxiety
Strategies	Description of a primary overall approach for constructing circuits on the physical breadboard	Methodical, trial and error, memorization, visualization
Tactics	Description of the breakdown of the process by step when constructing the circuit on the physical breadboard	Collect all resources first, check one connection at a time, double-check the circuit before energizing
Motivation	When the participant mentions his/her motivation for taking part in the study and persevering through the study	Relationship with researcher, intrinsic, incentive

Table 4.3. Properties and Dimensions for each of the Categories

Category	Properties	Dimension
Past experience with circuits	• Experience • Date of experience • Type of experience	• Limited to extensive • Long ago to recent • Informal to formal
General circuit knowledge	• Understanding • Type	• Rudimentary to advanced • Theoretical to practical
Characteristics of the learning environment	• Support • Engagement	• Low to high • Weak to strong
Attributions	• Attribution • Knowledge • Direction	• Internal to external • Declarative to procedural • Negative to positive
Self-descriptions	• Origin	• Innate to learned
Affect	• Valence • Arousal	• Negative to positive • Low to high
Strategies	• Process	• Unplanned to planned
Tactics	• State	• Mental to physical
Motivation	• Orientation • Level	• Extrinsic to intrinsic • Low to high

Results

Theme 1: Level of support

Participants in the simulated environments, specifically the 3D environment, often referred to higher levels of support in these environments compared to the physical environment. Participants who practiced in the 3D condition spoke of its specific attributes that benefitted them during practice such as the different views of the breadboard as well as the ability to zoom in and out. They specifically referred to this, saying:

> "I liked the, the virtual environment cuz you couldn't kind of, um, you didn't have a ... You could kinda flip it and view however you wanted. You didn't have this

> pure kind of, I guess, isometric view. You could look at it on the side. You could look at it in all sorts of, um, visual angles so it was easier to visualize the circuits in the virtual angle vers- er, in the virtual environment versus in the real world where you had to kinda ... Well, you can't, like, turn a circuit upside down, obviously, otherwise all the components would fall out and you have to start over again and you'd probably break some components."
>
> "Um, and I think that was much more difficult to discern from the physical breadboard than from the computer model. Um, again just that aerial view that you only have from the physical model was, I guess slightly uncomfortable. Whereas in the digital one you could manipulate and look at it from the side and zoom in."

Participants in the 2D and 3D conditions also referred to the simplicity of working in those environments. As one put it:

> "But, um, I was a lot faster on the computer than I was in real life, because I was trying to recall in my brain, like, "Okay, this was on the fifth hole," or whatever, and I had to, like, count it, and just, like, physically it was hard for me to, like, connect the pieces. Um, whereas, like, on the computer, it was easier, just, like, select where I wanted the wires to go, instead of having, like, make sure the wires would stretch to this hole, and make sure that they were in the holes all the way. Um, so the transition wasn't bad. Um, but I definitely preferred the CAD **[3D]** one to the physical one."

However, the primary difference in the level of support between the physical environment and simulated environment concerned the level of feedback. Participants in both the simulated environments, but more so in the 3D environment, benefitted greatly from the positive feedback they received while they were practicing.

> "I felt, again, that, um, that that positive reinforcement of knowing that like, okay I'm getting the answers right, I'm, you know, getting all these green lights in my drawing, my sketch or whatever and then it's like working in the simulation [3D]."
>
> "And that was one of my issues was – you know- making sure it was connected well enough in the physical environment so that that light could come on and that could -that sometimes made me second guess myself and wonder if I was actually putting it on correctly and wondering, "What did I do wrong?" Whereas, like I said, in the computer environment, you click go and if it's set up correctly, that light's going to come on. So, I really liked the feedback that I got from the computer environment [2D]"

However, participants also reflected on not having this feedback in the physical environment and how it influenced their performance. One participant summed up the issue well stating:

> "I think having the instant feedback that you get in the simulation [3D] when it turned red or green like when you're doing it that you know that it's hooked up right. Not having that in an actual like physical breadboard was tricky because like, oh, I don't know why this isn't working because you can't figure out where

> the problem is. So I think that was, I don't know, like the benefit in it may be like handicapped to like transitioning from the computer to the physical breadboard was that, that instant feedback of like not knowing, not knowing how to figure out where the problem was, if there was a problem."

Theme 2: Physical transition

Physical transition related to the strategies and tactics the participants used during the construction process on the physical breadboard as well as the participants' assessments of their struggles during this transition. In terms of strategy, in general participants described having some idea of how they wanted to approach to the task, but many switched to a trial and error approach at some point during construction, specifically if they encountered errors.

> "I didn't start with like, no clue. I started with like a base idea of what I wanted. Or like, what I could build off of it. But I also didn't start with like, "I know exactly what I'm gonna do."
>
> "Um, the only trial and error, I guess ... Part of the thought process that came in was when I had that one light bulb that didn't work, um, and I needed to make sure that, uh, it could; but everything other than that was very step by step, and very methodical. Um, I didn't really do a lot of trial and error until I came up with an error, and then I had to try to fix it."

Participants in the physical condition, however, described a more structured approach using phrases such as "being organized," "following instructions," and "planning." Participants in the simulated environments, on the other hand, appeared more comfortable with a less structured approach making statements such as “and then if I didn't, then, you know if it didn't work then I would just have to play around with it and just keep playing around with it and just rethink it until I got it,” and “'Um, but I kind of just tried things until it worked.” Participants from each condition also spoke about using memory of the circuits constructed during practice to guide their construction, with some even mentioning trying to recreate the circuit directly from memory.

In speaking of the step-by-step process followed during construction, participants described attempting to follow the process used during practice. One major difference between the tactics taken by participants in the physical condition compared to the participants in the 2D condition concerned visualization and mental rehearsal. Participants in the 2D simulation described trying to mentally construct the circuit they learned in that condition prior to attempting construction on the physical breadboard.

> “I actually constructed it in my mind through the simulator software and then took the simulator software and tried to implement it and copy it that same way. So, that was my process, more so, in my head, and then see if I could make my hands actually do that. So, yeah.”
>
> “Um, I just really tried to imagine it, um, and I think that what I did was I tried to set the things up in front of me the way that they were on the screen. And then just try to do everything the way that I did there.”

Participants in the physical environment made fewer but more positive attributions than participants in the simulated environments, and they made more positive ones. They spoke about how recent the practice was and of the helpfulness of the videos.

When discussing some of the reasons for their struggles, participants in the simulated environments spoke primarily of gaps in their procedural knowledge.

> “But I always felt that I can get it. Because I had the knowledge of doing it. Um, but there's something that either, I may have missed that. I, I felt that there was something more wrong with the breadboard or something that I was doing wrong, procedurally rather than what I had learned to do.”
>
> “Um, so I think the most frequent obstacle at least that I perceived was that I wasn't using the correct wires to complete the circuit. Or for whatever reason my arrangement of the different components on the breadboard were, were not right. Um, so I would try and go back to what I had learned the digital model”

Participants in the simulated environments also spoke of some difficulty related to manipulating components in the physical condition.

> “I think the, the, the main difference I think between the so the, you know, clicking and the 2-dimensional environment was easier because the components in the physical environment was, were so much smaller.”
>
> “I just found it, in this case, I found it harder because the components were small. If the components had the same sort of values, and they were just enlarged, um, by a scale of ... A factor of 5 or 10 say, it'd be a lot, a lot easier for me to work with.”

Another issue that impacted participants’ transition from the simulated environments to the physical environment was the orientation of the breadboard and the components. Below two participants note how the change in orientation impacted their affect and performance.

> “I do know that it annoyed me that the orientation was different but I don't, I guess I'm not a 100% sure whether or not it was the fact that the module and the simulation were flipped or the, or the simulation and the physical board were flipped…”
>
> “Um, I think just the orientation of some components like the switch uh, I don't recall precisely. But I think there is some ... I had trouble with the orientation of something.”

Theme 3: Emotional transition

Participants transitioning from the simulated environments to the physical environment described a wide range of emotions related to this transition. Some spoke of the downward shift of confidence that resulted from performing without obstacles in the simulated environment and then struggling to construct the circuit in the physical environment.

> “It took me a really long time. Be- uh, there was something related to ... I felt that I was very close every time I had it. Because I felt uh, uh, throughout the um, computerized part of that experiment, I got everything right away. And everything always worked right away.”
>
> “So, just after trying several times, it was like okay, probably I missed something. Probably I just don't get it, even though I'm supposed to get it. So, it was more

> like moving from, okay, excitement it's like, I can do this to like why? Why is this not working? It was more like a downward slope."

Participants also spoke of increased pressure and isolation in the physical environment stating:

> "I felt more pressure when it was actually in front of me."
>
> "So then in switching to the physical environment, like, all of that kinda like was chipped away so it's like I didn't have my notes, I didn't have any kind of feedback, it's really just me and these wires."

Participants, specifically in the 2D condition, spoke of "higher stakes" in the physical environment that lead to increased frustration during their struggles but also of greater satisfaction for those who were able to correctly construct the circuit.

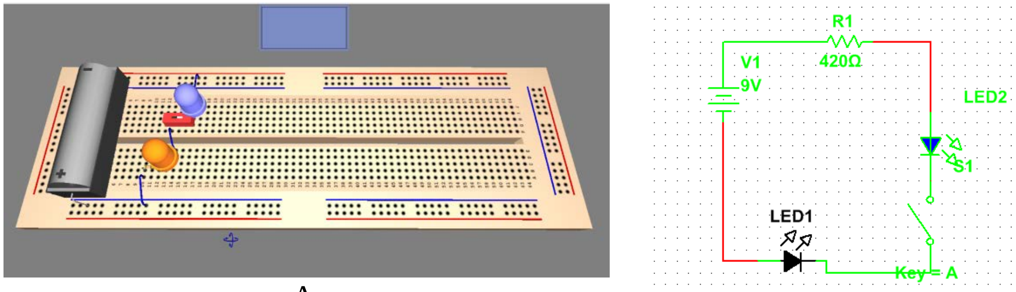
> "I think that the physical environment was more intimidating, ah, because it seemed as though um, even with relative success in the 2D environment, um, to touch the physical objects seemed to be um, a little, yeah, intimidating is the word. It, it just seemed to be, there seemed to be more pressure with ah, using the real objects."
>
> "Uh, the other thing I said was that when you go, when you do it physically, like the stakes feel a lot high, the emotional stakes felt a lot higher like you were more like down when something didn't work and you were more like excited when it did work and part of that might have been the fact that it was like physical so you're like hands on with it and some of it also might have been because it is more annoying, it takes longer to actually change something physically."

> “Well I think that ah, one of the things that I liked in the, in the more, in the, sort of in the tactile, in the physical environment is that um, you know, right or wrong, whatever the, whatever the process um, I think there's a way of seeing, like of actually experiencing success or failure. So, seeing the light comes on, um, while there may be more risk, more seeming risk, or you know, like um presumed risk, the, the reward is greater to actually physically make a light come on seems to be um, a better payoff than ah, a program you know in the 2 dimensional environment telling you that you've successfully completed it as opposed to, you know, sort of seeing the, the product of that.”

Discussion

Three themes emerged from the analysis, level of support, physical transition and emotional transition. The level of support focused on attributes of both simulated environments that helped the participants successfully complete the practice activities, specifically, positive feedback, zooming capabilities, alternate viewpoints and simple manipulation of components. The attribute of the learning environment seen as having the most influence on performance was feedback. In the 3D environment, participants were able to switch views between the circuit diagram and the breadboard to ensure that they were constructing the circuit correctly. The diagram used green lines for the correct connections and red for the incorrect ones (Figure 4.1). This feedback provided by the simulated environments appears to have both beneficial and detrimental effects.

Participants found it helpful to have feedback during the practice session, particularly in the 3D environment, as it provided visual information concerning the location of an error made while they were constructing a circuit on the virtual breadboard. However, the lack of feedback in the physical seemed to create two issues for participants: it hindered their ability to identify the source of the error when the circuit was not functioning and it reduced their willingness to troubleshoot. Extant literature has already identified this dual effect of feedback specificity, i.e. the amount of information provided to learners in feedback messages (Goodman & Wood, 2004), with previous studies suggesting that high feedback specificity is beneficial for immediate performance but reduces the learning opportunities needed for independent performance (Kensinger, 2004).



A.
Breadboard view

B.
Diagram view

Figure 4.1. Feedback Provided to Participants Working in 3D Breadboard Environment

The theme of physical transition focused on the approach participants used during the construction process on the physical breadboard and its effectiveness, rated on a scale ranging from methodical to trial and error. Most participants used an approach that fell somewhere in the middle; however, participants in the simulated environments appeared more comfortable using a trial and error approach than those using the physical breadboard. One possible explanation for this difference involves the adaptations required for the participants who transitioned from the simulated environments. Unlike the participants in the physical condition who did not have to adapt their performance, participants in the simulated environments were forced to deal with differences in the construction procedures, such as reading the resistor versus typing in the resistance value, making it difficult to follow the exact steps they used in the simulation. As a result, it was necessary for them to engage in trial and error during the process.

Participants in the 2D simulation spoke of visualization and mental rehearsal prior to actually constructing the circuit on the physical breadboard. They described trying to visualize the circuit they created in the simulation as well as trying to construct the circuit mentally in the simulation before attempting physical construction. These two additional steps in the construction process appeared to be a mechanism these participants used to recall the procedures they learned. The statements below describe more fully how these participants used visualization or mental rehearsal to help them build the circuit on the physical breadboard.

> “I actually constructed it in my mind through the simulator software and then took the simulator software and tried to implement it and copy it that same way. So, that was my process, more so, in my head, and then see if I could make my hands actually do that. So, yeah.”
>
> “Um, I just really tried to imagine it, um, and I think that what I did was I tried to set the things up in front of me the way that they were on the screen. And then just try to do everything the way that I did there.”

While working with and manipulating the small physical components created some issues, the orientation of the breadboard appeared to be particularly problematic. The orientation of the breadboard in the 2D simulation, which was horizontal, could not be changed, while the default orientation of the breadboard in the 3D environment, also horizontal, could be changed. For the physical construction, the breadboard was arranged vertically, but participants could, and several did, change the orientation. Participants who did not immediately change the orientation of the breadboard potentially experienced an unnecessary increase in cognitive load (Paas & Sweller, 2003). This increase in cognitive load may have been exacerbated for participants in the 2D conditions as they already had the additional task of translating “the representation from 2-D to 3-D” (Regian et al., 1992).

Another theme that emerged related to the affect of participants in the 2D simulation describes the affect of participants when they transitioned from the simulated environment to the physical one. Participants described two predominant emotional states related to this transition, a decrease in confidence and a heightened emotional divergence. Participants who performed successfully in the simulated environments during practice and then struggled in the physical condition described experiencing a “downward slope” of confidence. This drop in confidence was not simply the result of encountering obstacles but the feeling of being ill-prepared and unable to overcome these difficulties. Previous research has suggested that information processing capabilities are reduced when dealing with negative emotions (Heimbeck et al., 2003). More germane to this study, previous research in training has also found that learners who completed an instructional program without obstacles struggle when faced with challenges in the performance environment (Heimbeck et al., 2003). Goodman and Wood (2004) suggest that in order to generalize performance, learners have to be able to adjust to different performance conditions, including making errors and resolving them without assistance.

Participants in the 2D simulation also described a heightened emotional divergence when they transitioned from the simulated environment to the physical breadboard, indicating they became frustrated when they could not get the circuit to work in the physical condition, describing this feeling as increased “pressure.” They also described increased satisfaction and a “greater reward” when they were able to solve the circuit in the physical condition. For these participants, the perceived “stakes were higher” when they were working in the physical environment. Part of the reason for this feeling is summed up by one participant who described the 2D simulation as feeling “simulated.” Another participant, who also learned in the 2D environment, described the physical environment as “real.” As a result, the emotional intensity for these participants was lower in the simulated environments.

A second explanation deals with the task itself. Constructing a circuit on a breadboard is a hands-on task. Having to do this “hands-on” task in a simulated environment potentially detracted from both the emotional engagement in the environment as well as the participants’ perceptions of their ability to complete the task. This conclusion is supported by the previous study as participants in the simulated environments had statistically significantly lower self-efficacy than those in the physical environment (Alfred et al., 2016).

Limitations

Several months passed between the initial study and the follow-up study, and as a result, participants struggled to articulate the specific details related to their circuit construction process. Several of the participants knew the lead researcher outside of the study, situation that potentially affected the interview data. While a representative sample of 20 participants was interviewed, it may have been beneficial to conduct more interviews. In addition, the interviews were conducted by only one researcher.

Conclusions

The physical fidelity of the learning environment impacted the participants' attributions, affect, and strategies and tactics. Although most participants in the 2D simulation and 3D breadboard environments enjoyed working in those conditions, learning how to construct a circuit in either of those conditions contributed to procedural knowledge gaps, decreased ability to identify errors, and heightened levels of frustration that were detrimental to performance. Some participants noted these limitations, suggesting that the computer conditions might be best used to help students develop a conceptual understanding. However, those limitations may be resolved with improvements in the design of the software. Specifically, the design of 2D and 3D environments need to reduce the level of support provided to participants. For example, the 3D breadboard software could progressively decrease the feedback provided so that learners have the help they need early in practice but are not hindered as they prepare for the transition to the real world.

Both the 2D simulation and the 3D breadboard software could also facilitate the transition by requiring similar procedures to those in the physical environment. For example, allowing participants to choose the correct resistor by reading a resistance sheet is a more difficult task, than having to type in the resistance value. In addition, the simulated environments can make the participants aware of differences they may encounter when they transition. Transitions from these environments can be made more smoothly if participants are aware of such issues in the physical environment as blown LEDs, dead batteries, and burnt connections on the breadboard that do not occur in the simulated environments. If participants are knowledgeable of these potential issues, they can better troubleshoot issues in their construction.

However, some differences remain that require students to acclimate to the physical properties of the breadboard. One example is physically manipulating the components and inserting them properly into the breadboard as this process simply does not translate from the simulated environment. The other physical difference involves the orientation of the breadboard. A simple fix in the 2D simulation would be to allow participants' to orient the breadboard vertically or horizontally based on their preference. However, participants were able to overcome most of these differences as demonstrated in the initial study.

The other difference between the 2D and 3D environments and the physical one concerned the participants' affect while working in the simulated environments. Participants described feeling "intimidated," "more pressure," and having "higher stakes," when transitioning from the simulated environments to the physical one. While the 2D and 3D simulations cannot necessarily change these emotions, they can help build confidence and self-efficacy by providing learners with the knowledge needed for both constructing a circuit in that environment and for transitioning to a physical breadboard. Based on the experiences described by the participants as well as results from the initial study, both the 2D and 3D environments had strengths and weaknesses that shaped participants' performance. Improvements in the design along with the advantages of the software – specifically, ease-of-use, multiple views, zooming capabilities, positive feedback – can offer a superior learning experience for students while also supporting high transfer.

Chapter Summary

The second aim of the research for this dissertation was to explore how the physical fidelity of the learning environment contributed to the differences in proficiency found in the previous study. The analysis found that the physical fidelity of the learning environment impacted the participants' attributions related to their performance, their affect during the construction task, and the strategies and tactics they used when constructing the circuit on the physical breadboard. Although most of the participants using the 2D and 3D simulations enjoyed practicing in those environments, learning to construct a circuit in those environments contributed to procedural knowledge gaps, decreased ability to identify errors, and heightened levels of frustration, all of which were detrimental to their performance.

CHAPTER FIVE

DISSERTATION STUDY THREE

Purpose

The purpose of the study was to evaluate the retention of individuals learning in different levels of physical fidelity as defined in research aim three. To address this goal, a 4-week longitudinal study was conducted.

Methods

Leveraging the results of Study 1

Improvements in the instructional design of the video lecture, practice exercises, and activities were made based on issues discovered in the first study. These changes included breaking the 28 minute video lecture into three shorter videos with 2-3 practice exercises after each section. These changes also included providing opportunities for participants in all conditions to become comfortable determining the resistance value of through-hole resistors and providing participants in the simulated environments with transition notes to help them understand differences they may encounter when working with physical circuits (Appendix K).

Participants

This study included a total of 70 participants, both undergraduates and graduate students. However, students who completed an electrical circuits course in the past academic year were not eligible to participate. In addition, participants had to be able to self-report their SAT or ACT scores. Participation was voluntary, and the participants received a $20 gift card for each session they participated in. A majority of the participants (n=64, 91.4%) were undergraduates, with a mean age of 20.27 (SD=2.28). Females accounted for 61.4% of the participants, and 60 participants (85.7%) reported having very little to no experience prior experience working with circuits. This study was approved Clemson University IRB (IRB2016-041).

Experimental design

This study used a 3 x 3 repeated measures design with the level of physical fidelity (2D, 3D, and physical) as the between-subjects factor and the measurement occasion (T0, T1, T2) as the within-subjects factor. Pretest scores, cognitive ability, and goal orientation were used as covariates in the analysis. The dependent measures for this study included self-efficacy, gain scores (score), circuit design (grade), circuit time and construction (grade), which was scored as "no errors," "minor errors," and "major errors."

Participants' SAT or ACT scores were used as measures of cognitive ability, with the ACT composite scores being converted to total SAT scores for these 10 participants using the equivalence chart developed by Dorans (1999). Both goal orientations, LGO and PGO, were assessed using an eight-question instrument developed by Button et al. (1996). The reliability for these questionnaires was $\alpha = 0.72$ for PGO and $\alpha = 0.78$ for LGO. Post instruction self-efficacy was assessed using a six-question instrument with a Cronbach's alpha of $\alpha = .82$ (Guthrie & Schwoerer, 1994). The questions for all of these instruments used a five-point Likert scale ranging from strongly disagree to strongly agree.

Procedures

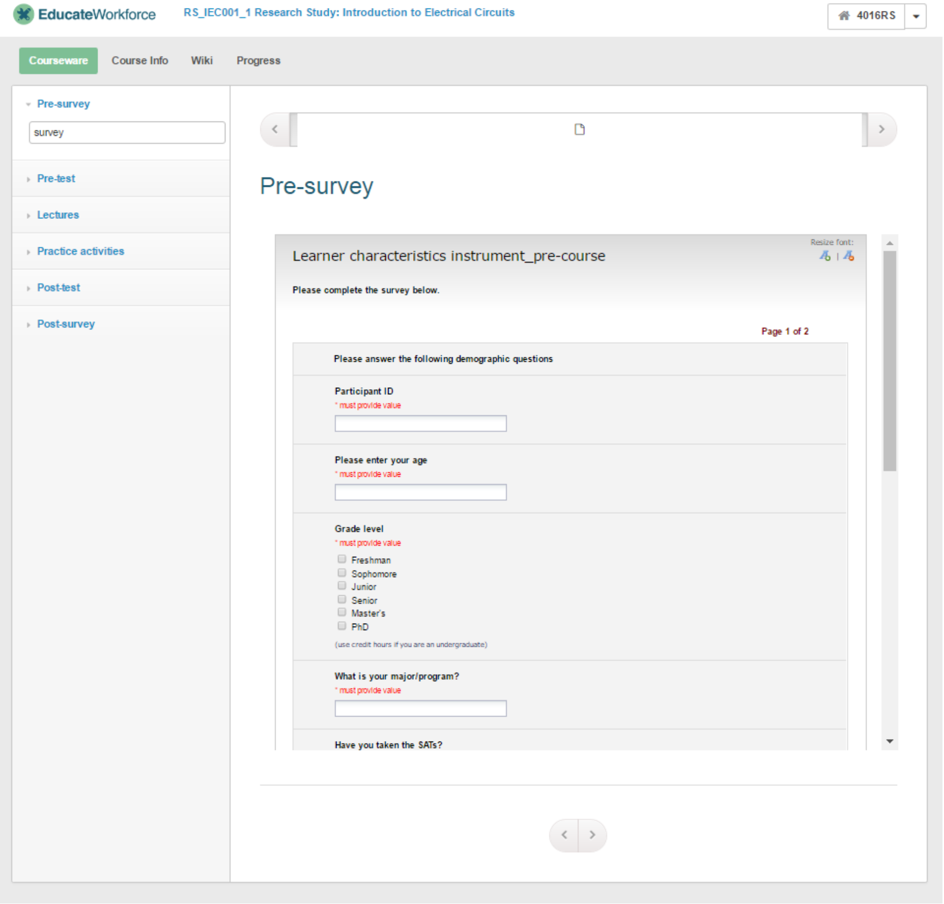
Upon arrival to the study location, participants first completed the consent form, after which the researcher explained the study procedure and gave the participants their user IDs for logging into the learning management system, Educate Workforce, which housed the course material for the study (Figure 5.1). Once the participants were logged in, they completed a survey that included demographic questions and goal orientation questions (Appendices B and C). Participants also reported their SATs or ACT scores on the demographic survey instrument. Next, the participants completed a five-question online pretest (Appendix A) that included questions related to electrical circuit concepts (e.g., voltage, resistance, and current), circuit diagrams and symbols, breadboard functionality, and Ohm’s law. Each question had four answer options.

After the pretest students watched a 3 brief video lectures, totaling 28 minutes, which covered basic circuit analysis. Participants also completed 2-3 practice questions related to the topics covered in each lecture.   These practice questions were graded immediately by the system and feedback, including the correct answer, was provided. Following the presentations, the participants were given the opportunity to practice constructing a circuit on a breadboard based on their assigned condition. Those assigned to the 2D simulation condition used an Arduino 2D breadboard from 123D Circuits (123d.circuits.io), while those assigned to the 3D condition practiced constructing a circuit using National Instrument Multisim Educational Edition version 13, and participants in the physical condition practiced using a 800 point solderless breadboard. These were the same breadboards used in first study.

Through videos, participants were shown how to use Ohm’s law to calculate the resistance values needed for series and parallel connections, how to translate a specified circuit into a diagram, and how to construct a circuit using the physical or simulated breadboards. Because students in the 2D and 3D conditions also had to learn to use the software, the instructional videos for each of the conditions varied in length. In total, this study involved six videos, 2 for each condition, ranging from 7 to 17 minutes.

The equipment for this study included a computer workstation with dual monitors to allow participants to construct their circuits as they watched the demonstrations (Figure 5.2). In the 2D and 3D environments, participants navigated using the mouse and keyboard. Participants in the all three conditions had comparable components LEDS, resistors, batteries, and switches for constructing their circuits during the practice sessions.

Participants were given three practice activities to complete. During these practice sessions, they were provided with feedback on the accuracy of their calculations and the construction of the circuit and were referred to the appropriate video for review for any errors they made. The participants were not allowed to continue the experiment until they successfully completed the practice activities. Although this requirement led to varying practice times, it was essential that participants demonstrate a minimum level of proficiency before continuing to the construction task. Following these practice sessions, the participants completed a survey assessing their post instruction self-efficacy and a 5-question multiple choice, online posttest (Appendices D and E). The posttest was of the same structure and length as the pretest and used similar questions.



Pre-survey

Learner characteristics instrument_pre-course

Please complete the survey below.

Page 1 of 2

Please answer the following demographic questions

Participant ID
* must provide value

Please enter your age
* must provide value

Grade level
* must provide value
☐ Freshman
☐ Sophomore
☐ Junior
☐ Senior
☐ Master's
☐ PhD
(use credit hours if you are an undergraduate)

What is your major/program?
* must provide value

Have you taken the SATs?

Figure 5.1. Educate Workforce Student Dashboard

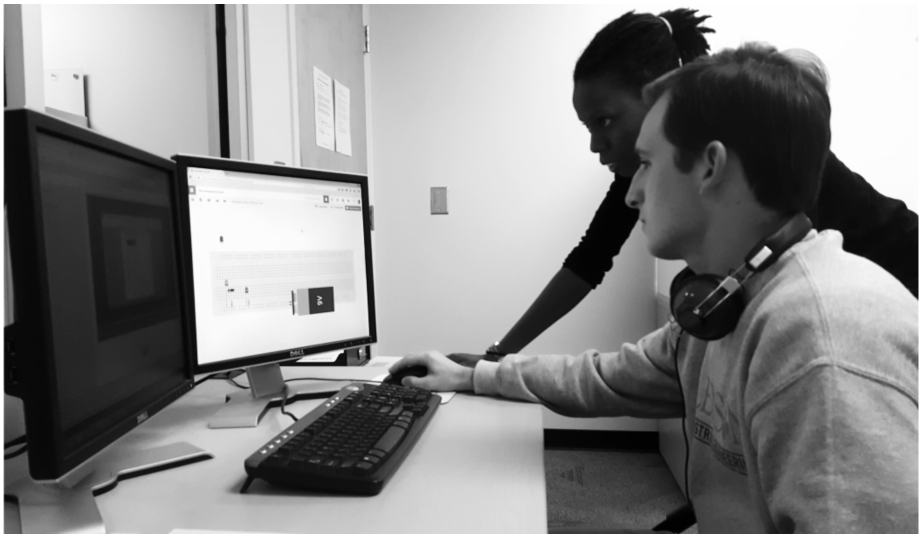


Figure 5.2. Setup of study for 2D and 3D participants

Participants in all conditions then constructed a circuit on a physical breadboard (Appendix F). During this task, they did not have access to their notes or the instructional videos.   During the construction, participants were video recorded using a GoPro Hero4 Black camera, which was positioned above the construction area. Once the students completed this activity, they were thanked for their participation and given a gift card.

At the two-week (T1) and four-week (T2) intervals following the initial training, participants returned to complete an additional posttest and construction task (Figure 5.3). The circuit constructed for T1 was a circuit with two LEDs and one switch such that the it alternated power between the LEDs (Appendix G). For T2, the circuit involved three LEDs and one switch such that two LEDs were connected in series and the third was powered by the switch (Appendix H). The test format for T1 and T2 were the same as for T0 – five questions with four answer choices (Appendices I and J). Four of the questions for both posttests were comparable to the questions in the initial posttest. The new question for the T1 posttest asked participants to identify the circuit diagram for a described circuit, while the new question for T2 asked participants to identify the issue with a constructed circuit using two images. In addition for both T1 and T2, participants completed a brief survey asking whether they had practiced building circuits or learned more about circuits after T0 and T1, respectively. The T1 times for participants ranged between 12 and 15 days. For the T2 participants they ranged from 26 to 29 days.

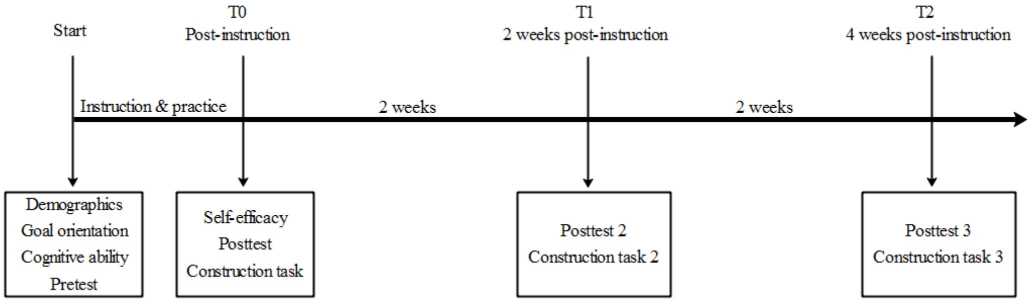


Figure 5.3. Timeline of Procedures for Dissertation Study

Results

Analysis

The data analysis was conducted using SPSS 22. Prior to analysis, the data was evaluated to verify that it met the assumptions for an ANOVA. All analysis was conducted at the alpha =.05 level. Outliers were identified using residuals, leverage values and Cook's Distance.

T0. ANOVAs were used to determine the main effects of the IVs (physical fidelity) and covariates (cognitive ability, pretest scores, and goal orientation) on self-efficacy, gain score, circuit design, circuit construction, and construction time. To facilitate interpretation, continuous variables were categorized using median splits.

T1 – T2. Mixed model ANOVAs were used to determine the main effects of the IVs (physical fidelity and time) and covariates (cognitive ability, pretest scores, goal orientation, and engagement) on posttest scores, circuit design, circuit construction, and construction time. Mixed models were used because the analysis included both between subject and within subject variables.

For the retention analysis, only participants who were able to construct the circuit correctly were invited to return for T1 and T2. Of the 70 participants in the study, 50 participants (71.4%) met the minimum proficiency requirements. However, only 40 participants continued for the retention analysis --14 participants in the physical condition, 14 in the 2D condition and 12 in the 3D condition. Each participant completed three sessions except for one who missed the second session and one who missed the third session. Before T1 and T2, participants completed a two question retention survey to determine whether they continued to learn about circuit concepts or practice constructing circuits during the retention periods. The majority of these participants 37 (92.5%) were undergraduates, with a mean age of 20.18 years old (SD=2.15). Females accounted for 50% of the participants. Approximately 83% (n=33) reported having very little to no experience prior experience working with circuits.

T0 Results

A one-way ANOVA found no significant differences in the pretest scores of participants in the three conditions, *F*(2, 69) = .945 p =.394. The one participant who failed to report her SAT/ACT score was not included in this and subsequent analysis.

Self-efficacy (SE). One outlier was found and removed from the analysis, and one participant did not complete the SE instrument for a total of 67 data points. The analysis found no significant differences in the mean SE of the participants in the three conditions, *F*(2, 66) = 2.53, p =.084.

Gain score. The mean pretest scores for all participants was .43 (SD = .22), and the mean posttest score was .71 (SD =.25) for an average gain of .29 (SD =.26). Only the pretest score was a significant predictor of gain score, *F* (1, 63) = 19.72, p =.003, (Table 5.1). Participants with a low pretest score (.40 or less) achieved higher gains than participants with a high pretest score (above .40) (Table 5.2). The unique effective size for pretest scores was sr^2 = .115.

Design score. Four participants did not complete the design task. Two of these participants withdrew from the study, and the other two could not complete the practice activities and were withdrawn by the researcher. Two outliers were also removed from the analysis. The mean design score for T0 was 87.31 (SD = 12.73). Only cognitive ability, *F*(1,59) = 9.42, p =.012, was a significant predictor of design score (Table 5.3). Participants with high cognitive ability scored 8.74 points higher than participants with low cognitive ability (Table 5.4). The effect size for cognitive ability was sr^2 = .083.

Table 5.1. ANOVA for Gain Score

Parameter	Sum of Squares	df	Mean Square	F	P-value
Intercept	1.609	1	1.609	29.097	.000
Fidelity	.290	2	.145	2.620	.081
Pretest scores	**.525**	**1**	**.525**	**9.493**	**.003**
LGO	.060	1	.060	1.078	.303
Cognitive ability	.168	1	.168	3.041	.086
Error	3.485	63	.055		
Total	4.577	68			

R Squared = .239 (Adjusted R Squared = .178)

Table 5.2. Comparison of Pretest Scores for Gain Scores

			95% Confidence Interval	
	Mean	Std. Error	Lower Bound	Upper Bound
Low pretest score	.354	.036	.282	.426
High pretest score	.172	.047	.078	.265

Table 5.3. ANOVA for Design Score

Parameter	Sum of Squares	df	Mean Square	F	P-value
Intercept	479524.76	1	479524.76	2331.019	.000
Cognitive ability	**1194.23**	**1**	**1194.23**	**5.805**	**.019**
LGO	143.46	1	143.45	.697	.407
Condition	794.99	2	397.50	1.932	.154
Error	12137.16	59	205.71		
Corrected Total	14430.98	63			

R Squared = .159 (Adjusted R Squared = .102)

Table 5.4.Comparison of Cognitive Ability for Design Score

			95% Confidence Interval	
	Mean	Std. Error	Lower Bound	Upper Bound
Low cognitive ability	82.20	2.55	77.09	87.31
High cognitive ability	90.94	2.54	85.84	96.03

Construction time. Four participants did not complete the construction activity, meaning a total of 65 observations were analyzed for construction time. The mean construction time was 19.60 minutes (SD =10.16) (Table 5.5). The ANOVA conducted found significant differences in construction time among participants based on fidelity, *F*(2, 58) = 4.70, p =.013, and cognitive ability, *F*(2, 58) = 7.06, p =.010 (Table 5.6). Post hoc analysis conducted using LSD found significant differences in construction time between participants in the physical condition and those in the 2D condition (p=.007). Participants with high cognitive ability constructed their circuits 6.54 minutes faster than participants with low cognitive ability (Table 5.7). The effect size for fidelity was sr^2 = .214, and the effect size for the cognitive ability was sr^2=.093.

Table 5.5. Mean Construction Time per Condition

Condition	Mean	Std. Deviation	N
Physical	15.18	6.51	22
2D	23.19	9.98	21
3D	20.59	11.97	22
Total	19.60	10.16	65

Table 5.6. ANOVA for Construction Time

Parameter	Sum of Squares	df	Mean Square	F	P-value
Intercept	24583.93	1	24583.93	283.17	.000
Fidelity	**816.43**	**2**	**408.22**	**4.70**	**.013**
Cognitive Ability	**613.05**	**1**	**613.05**	**7.06**	**.010**
LGO	86.57	1	86.57	.997	.322
Condition * LGO	133.41	2	66.71	.768	.468
Error	5035.44	58	86.82		
Total	6609.60	64			

R Squared = .238 (Adjusted R Squared = .159)

Table 5.7. Contrast for Cognitive Ability for Construction Time

	Mean	Std. Deviation	N
Low cognitive ability	22.82	11.37	33
High cognitive ability	16.28	7.57	32

Construction. A multinomial logistic regression model found that design score ($\chi2$ (2, N = 63) = 8.35, p=.005) and fidelity ($\chi2$ (2, N = 63) = 7.33, p=.026) were significant predictors of correct circuit construction (Table 5.8). The odds of constructing a circuit without errors were 6.93 times higher [95% CI: .1.64, 35.41] for participants in the 2D condition. The odds of constructing a circuit with no errors for participants with high design scores were 5.21 times higher [95% CI: .1.63, 18.65] than for participants with low design scores (Table 5.9).

Table 5.8. Tests of Model Effects for Design Score

Parameter	Likelihood Ratio χ2	df	P-value
Fidelity	**7.33**	**2**	**.026**
Cognitive ability	3.19	1	.074
Design score	**7.87**	**1**	**.005**
Construction time	2.17	1	.141

Table 5.9. Parameter Estimates for Design Score

Parameter		B	Std. Error	Hypothesis Test			Exp(B)	95% Profile Likelihood Confidence Interval for Exp(B)	
				Wald χ2	df	P-value		Lower	Upper
Threshold	Major errors	.347	.707	.241	1	.623	1.42	.357	5.94
	Minor errors	2.09	.754	7.67	1	.006	8.07	1.92	38.05
2D		**1.94**	**.775**	**6.24**	**1**	**.012**	**6.93**	**1.64**	**35.41**
3D		.775	.669	1.34	1	.247	2.17	.600	8.48
High cognitive ability		.916	.517	3.14	1	.076	2.50	.915	7.03
High design score		**1.65**	**.616**	**7.20**	**1**	**.007**	**5.21**	**1.63**	**18.65**
High construction time		-.782	.539	2.12	1	.145	.458	.155	1.29

T0 – T2 Results

Posttest scores. The first learning outcome assessed over time was the posttest scores. Two participants were removed from this analysis as a result of their responses on the retention survey. A baseline model was run to calculate the overall mean of participants’ posttest scores and the intraclass correlation (ICC), which measures the percentage of the total variance between persons (intercept) and within persons (residual). This model found that 30% of the variation occurred between subjects. Multilevel analysis found that cognitive ability, *F*(1,40) =4.14, p=.048, and measurement occasion, *F*(2, 34) =9.12, p=.001, were significant predictors of posttest scores (Table 5.10). Participants with high cognitive ability scored an average of 10.40 points higher than participants with low cognitive ability (Table 5.11). At T1, participants scored 17.37 points lower than participants at T0. Participants decreased by an additional 0.52 points at T2 (Figure 5.4). Post hoc analysis conducted using LSD found that the differences in means were significant between T0 and T1 (p=.001) and between T0 and T2 (p=.001).

Table 5.10. Test of Model Effects for Posttest Scores

Parameter	Numerator df	Denominator df	F	P-value
Intercept	1	56.34	532.39	.000
Cognitive ability	**1**	**40.44**	**4.14**	**.048**
LGO	1	40.44	.247	.622
Fidelity	2	40.44	.505	.607
Measurement occasion	**2**	**32.58**	**9.12**	**.001**

Table 5.11. Parameter Estimates for Posttest Scores

Parameter	Estimate	Std. Error	df	T	P-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	81.50	5.29	39.46	15.42	0.00	70.81	92.19
Cognitive ability	**-10.40**	**5.11**	**40.44**	**-2.04**	**0.05**	**-20.72**	**-0.08**
LGO	-2.78	5.60	40.44	-0.50	0.62	-14.10	8.53
2D	-0.26	6.60	40.44	-0.04	0.97	-13.60	13.07
3D	5.31	6.07	40.44	0.88	0.39	-6.95	17.57
T1	**-17.37**	**4.81**	**33.78**	**-3.61**	**0.00**	**-27.15**	**-7.58**
T2	**-17.89**	**4.72**	**33.04**	**-3.79**	**0.00**	**-27.50**	**-8.29**

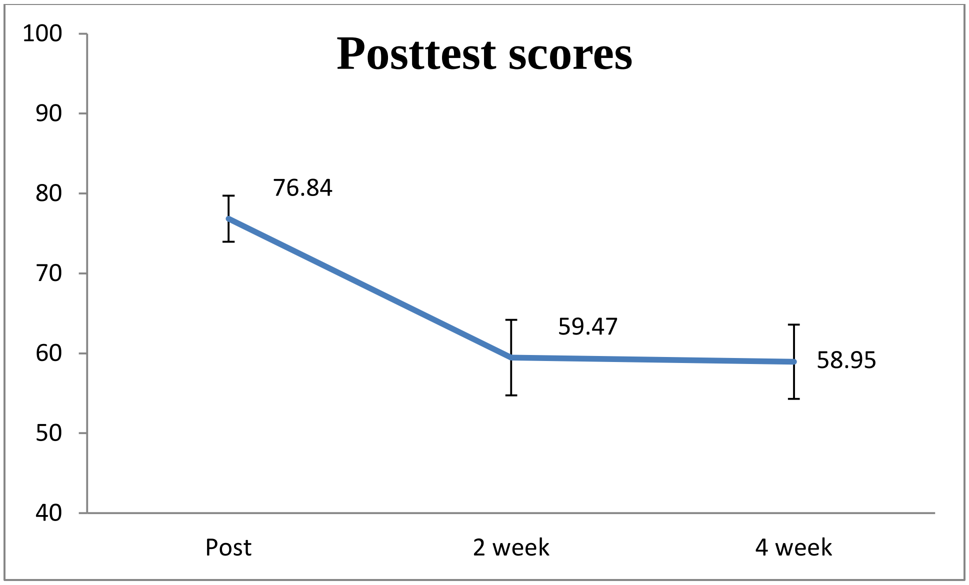


Figure 5.4. Posttest scores based on measurement occasion

Design score. For the analysis of the design score, one outlier was removed and two additional participants were removed based on the retention survey (the same two removed from the previous analysis). The ICC for design scores was 4.6%. Measurement occasion was a significant predictor of this score, *F*(2, 33) = 20.604), p<.001 (Table 5.12). The mean score at T0 was 90.09, and participants lost 11.06 points at T1 and another 8.27 points at T2 (Table 5.13). Post hoc analysis conducted using LSD found significant differences between the design scores at T0 and T1 (p<.001), T0 and T2 (p<.001), and T1 and T2 (p<.007).

The interaction between measurement occasion and fidelity, *F*(4, 43) = 4.77, p =.003, was also a significant predictor of design score (Table 5.12). In the physical condition, participants had the highest mean design score (96.79, SD = 2.08) initially, but this score declined steeply after two weeks (72.25, SD = 14.65) and again after 4-weeks (65.92, SD = 21.74) so that these participants had the lowest scores at the end of the retention period (Figure 5.5). The design scores for participants in the 2D condition decreased more steadily from 88.15 (SD = 11.13) at T0 to 78.08 (SD = 17.22) at T2. In the 3D conditions participants' scores were fairly consistent after two weeks, 84.46 (SD=9.85) to 83.13 (12.50) but declined significantly after four weeks to 69.92 (SD=16.69).

Table 5.12. Tests of Fixed Effects for Design Score

Parameter	Numerator df	Denominator df	F	P-value
Intercept	1	38.161	2502.771	.000
Measurement occasion	2	41.789	24.239	.000
LGO	1	31.507	.047	.830
Cognitive ability	1	31.567	2.664	.113
Fidelity	2	39.094	.252	.779
Fidelity * Measurement occasion	4	54.182	5.899	.001

Table 5.13. Mean Design Score Based on Measurement Occasion

Measurement occasion	Mean	Std. Deviation	N
T0	89.76	9.96	37
T1	78.31	13.73	36
T2	71.10	18.92	36
Total	79.81	16.43	109

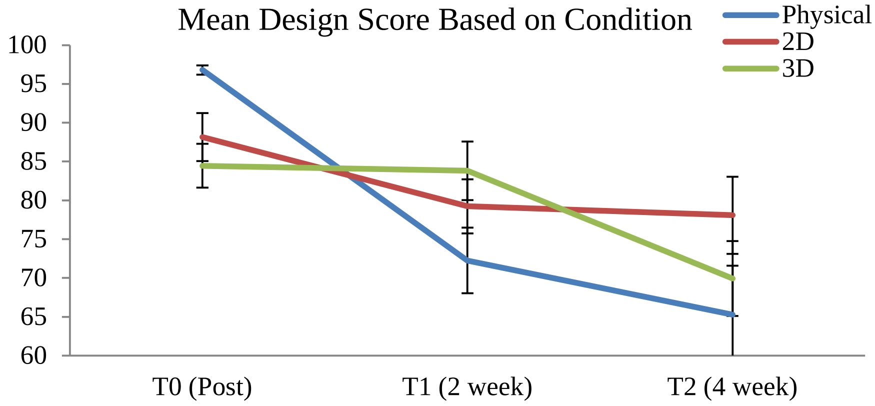


Figure 5.5. Interaction between fidelity and measurement occasion for design score

Table 5.14. Parameter Estimates for Design Score

Parameter	Estimate	Std. Error	df	t	P-value	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	98.81	2.91	31.76	33.99	0.00	92.89	104.74
T1	**-24.54**	**3.75**	**39.55**	**-6.55**	**0.00**	**-32.11**	**-16.97**
T2	**-31.50**	**5.15**	**43.39**	**-6.11**	**0.00**	**-41.89**	**-21.11**
Low LGO	0.65	2.99	31.51	0.22	0.83	-5.44	6.73
Low Cognitive ability	-4.48	2.74	31.57	-1.63	0.11	-10.07	1.11
2D	-9.44	3.76	30.91	-2.51	0.02	-17.10	-1.77
3D	-12.33	3.55	29.64	3.-48	0.00	-19.58	-5.08
2D * T1	**15.62**	**5.19**	**39.55**	**3.01**	**0.01**	**5.12**	**26.12**
3D * T1	**23.52**	**5.39**	**40.14**	**4.36**	**0.00**	**12.63**	**34.41**
2D * T2	**21.42**	**7.26**	**44.08**	**2.95**	**0.01**	**6.79**	**36.04**
3D * T2	**16.96**	**7.29**	**43.39**	**2.33**	**0.03**	**2.27**	**31.65**

Construction time. The overall mean for construction time was 26.29 minutes (SD =16.9), and the ICC for construction time was 26.5%. Only cognitive ability, *F*(1, 35) = 8.96, p =.005, was a significant predictor of construction time over the measurement occasions (Table 5.15). Participants with lower cognitive ability took an average of 9.8 minutes longer to construct their circuits than participants with high cognitive ability (Table 5.16).

Table 5.15. Fixed Effects for Construction Time

Source	Numerator df	Denominator df	F	P-value
Intercept	1	40.97	230.55	.000
Measurement occasion	2	30.27	1.41	.260
Cognitive ability	**1**	**35.08**	**8.96**	**.005**
LGO	1	35.12	.000	.983
Fidelity	2	40.63	.995	.379
Fidelity * Measurement occasion	4	30.90	.949	.449

Table 5.16. Parameter Estimates for Construction Time

Parameter	Estimate	Std. Error	df	t	P-value	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	14.14	3.74	28.19	3.78	0.00	6.48	21.80
T2	6.14	4.38	27.67	1.40	0.17	-2.84	15.13
T1	8.71	4.67	32.73	1.87	0.07	-0.78	18.21
Low Cognitive ability	**9.80**	**3.28**	**35.09**	**2.99**	**0.01**	**3.15**	**16.45**
Low LGO	0.08	3.47	35.12	0.02	0.98	-6.98	7.13
3D	8.69	4.81	23.46	1.81	0.08	-1.25	18.63
2D	7.06	4.67	23.84	1.51	0.14	-2.58	16.69
2D * T1	-9.43	6.60	32.73	-1.43	0.16	-22.86	4.01
2D * T2	-10.87	6.20	27.69	-1.75	0.09	-23.57	1.83
3D * T1	-3.49	6.99	33.84	-0.50	0.62	-17.70	10.72
3D * T2	-6.56	6.36	27.11	-1.03	0.31	-19.61	6.48

Construction. At T0, 24 participants made no errors, and 16 made minor errors. None of the 20 participants who made major errors at T0 participated in T1 or T2. From T0 to T1, 78% of the participants who made no errors at T0 also made no errors at T1 (Figure 5.6). One participant who made no errors in T0 did not participant in T1. Of the participants who minor errors at T0, 69% made no errors at T1. Four participants (25%) who made minor errors at T0 made major errors at T1. Only 9% of participants made major errors at T1 after making no errors at T0.

At T1, 28 participants made no errors, 4 participants made minor errors, and 6 participants made major errors. From T1 – T2, 68% of the participants who made no errors at T1 did not make errors in T2 (Figure 5.7). All four participants who made minor errors at T1 made no errors at T2. None of the participants who made no errors at T1

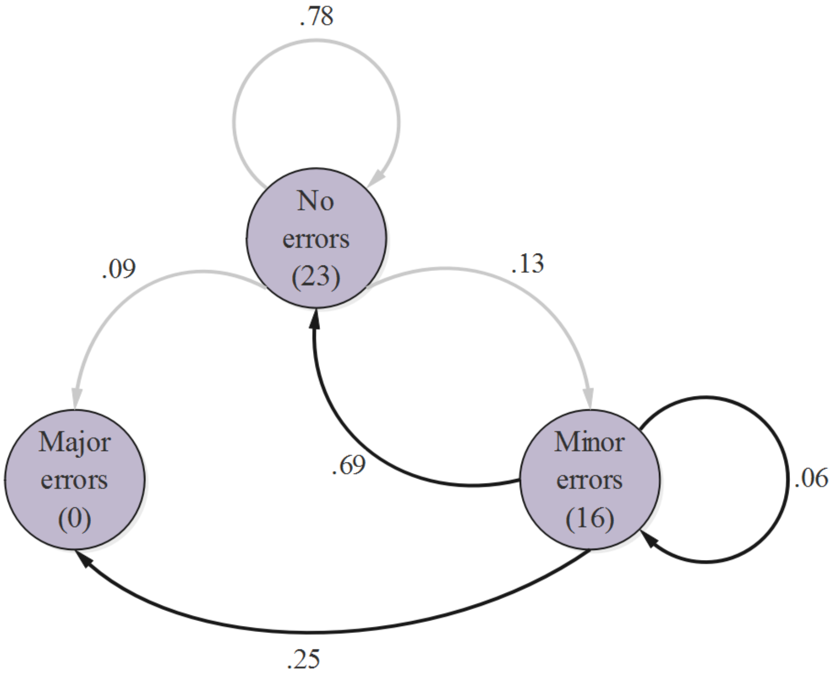


Figure 5.6. Transitions Between Error Categories from T0 (post) – T1 (2-week)

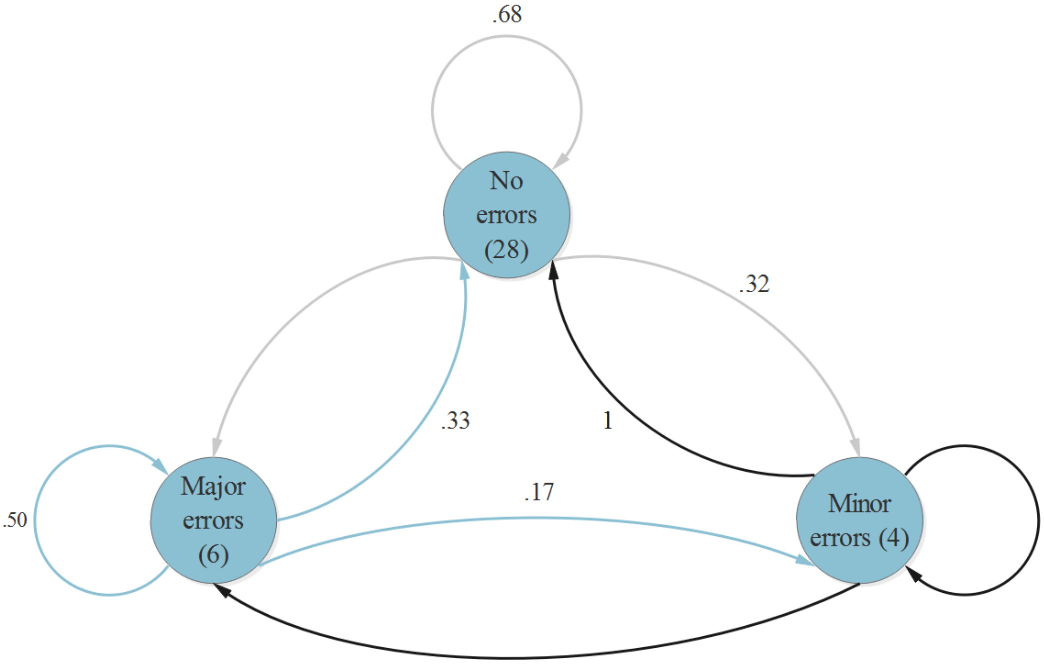


Figure 5.7. Transitions Between Error Categories from T1 (2-week) – T2 (4-week)

major errors at T2. Half of the participants who made majors errors at T1 also made major errors at T2, 33% made no errors and 17% made minor errors. A multilevel multinomial logistic regression for construction found that only LGO, *F*(2, 100) =3.532, p =.033, was a significant predictor of construction over time (Table 5.17). Participants with a lower than average LGO had 0.058 lower odds [95% CI : 0.004, 0.785] of constructing their circuit without errors during the retention period.

Table 5.17. Fixed Effects for Circuit Construction

Source	Numerator df	Denominator df	F	P-value
Model	12	104	1.28	.240
Measurement occasion	4	104	1.20	.315
Cognitive ability	1	88	0.71	.496
LGO	**2**	**104**	**3.53**	**.033**
Fidelity	4	92	1.93	.112

Discussion

T0

This study investigated how learning in different levels of fidelity influenced retention outcomes, an area that has seen little to no previous research. To explore this issue, it first evaluated learning outcomes post-instruction before looking at the learning outcomes again after 2-week and 4-week intervals.

Self-efficacy is an important learning outcome as it affects an individual's effort and persistence concerning a particular task (Zimmerman, 2000). Fidelity was not found to be a significant predictor of this outcome, perhaps because of improvements in instructional design. For example, in this study, all participants had the opportunity to practice determining the value of the resistors and learned about differences between working in the simulated and physical environments. These changes may have helped participants feel more prepared to work in the physical environment.

In this study, only pretest scores were significant predictors of gain scores. In general, posttest scores were higher than pretest scores for the participants, with participants with lower pretest scores achieving higher gains across all conditions (Table 5.2). Similar to SE, these differences were potentially the result of improvements in the design of the instruction. In the study, the practice questions the participants responded to were in a separate section. If they answered incorrectly, the correct answer was provided along with an explanation and a note about where to find the information in the video lecture. This change allowed participants to become more active in their learning, potentially helping them learn the material better and reducing the impact of cognitive ability (Prince, 2004).

Only cognitive ability was a significant predictor of design score. The circuit participants were required to design was a bit more complex than the ones used during practice. As a result, although most participants probably understood how to draw a circuit diagram in general, those with higher cognitive ability were able to draw the required diagram with minor or no errors. This finding supports research on far transfer which found that participants with higher intellect are better able to apply principles and concepts they have learned to novel situations (Clark & Voogel, 1985).

Participants in the physical condition constructed their circuits faster than participants in the 2D conditions. Participants who practiced with physical components had the benefit of a higher level of fidelity, which facilitated the transition from practice (Goldstein & Ford, 2002). The identical elements theory posits high positive transfer when the instruction environment is identical to the performance environment as learners are basically practicing the task which they will need to perform (Yamnill & McLean, 2001). Participants in the 2D and 3D conditions probably needed time to acclimate to the nuances of working with physical components. Some of these nuances, which were specifically described in the second study, included working with the smaller components, having to physically manipulate components and insert them properly in the breadboard, and adjusting to the breadboard orientation (Alfred, Lee, Neyens, & Gramopadhye, 2016).

In terms of circuit construction, participants in the 2D condition in this study exhibited higher odds of constructing their circuits without errors than the participants in the other two conditions. This finding was not expected as identical elements theory suggests that, similar to construction time, participants in the physical condition should have the advantage because they practiced using a physical breadboard. Based on the construction time, however, it is possible that participants in the 2D condition spent more time working to submit their circuit without errors. So it appears that while 2D participants took more time to construct their circuits, they constructed them correctly at a rate comparable to, if not higher, than participants learning in the physical environment.

Overall, this study found significant improvements in learning outcomes for the participants in the simulated environments. Revisions in the instructional design that included making participants active learners and using scaffolding techniques potentially contributed to increased self-efficacy, reduced construction time, and a higher success rate for participants learning in the simulated environments.

T0 – T2

Of the 50 participants who completed their circuits with no or minor errors who were invited to participant in the second part of the study, 40 participants completed the 4-week retention analysis. The non-qualification rate (20 out of 70) was highest in the 3D condition (12) and it was also higher for women (15) than for men (5). One possible cause for this is that the complexity of working in the 3D environment may have increased the cognitive load for participants with limited experiences working in that type of environment and the majority of women (60%) reported having little to no experience working in the 3D environment. Differences in attrition could be related to the lower spatial abilities of women (Feng, Spence, & Pratt, 2007). Women also exhibit lower self-efficacy for engineering tasks (Marra et al., 2009). This may have also influenced their perseverance and effort (Zimmerman, 2000). There were 10 additional participants who qualified but elected not to return for the retention analysis. This resulted in a dropout ratio of 20% which is not uncommon in longitudinal analysis.

The results found that the posttest scores exhibited a steep decline in retention during the first two weeks, with the decay leveling off at the 4-week period. Design scores decreased overall, but the rate of decline was different across the three conditions.

Construction time was not significantly different across measurement occasions, and circuit construction was fairly consistent.

The posttest scores indicated that measurement occasion and cognitive ability were significant predictors. Participants' scores decreased by 16.5 points in 2-weeks and by another point two weeks later as most participants incorrectly answered questions related to the application of Ohm's law and breadboard functionality. The trend in the decrease of posttest scores was consistent with a typical decay curve which exhibits rapid loss immediately after acquisition but a slower loss as the retention period increases (O'Hara, 1990). Participants with high cognitive ability scored an average of 10 points higher than participants with low cognitive ability, a finding consistent with past research which has shown that cognitive ability is related to both learning and retention (Clark & Voogel, 1985). Participants with high cognitive ability learn more and retain more than participants with lower cognitive ability regardless of the learning environment.

The second cognitive outcome assessed was design score. Measurement occasion and the interaction between measurement occasion and fidelity were significant predictors. Overall, participants' design scores decreased during the 4-week retention period and there was greater variation in the scores than at T0. Like the posttest, participants scores decreased because they were not applying Ohm's law correctly and also because they did not draw the diagram as specified. This result is consistent with research that has found decay in cognitive learning outcomes (Arthur et al., 1998). However, this decay curve did not follow the same pattern exhibited by the posttest scores due to a moderation effect. The decrease in design scores at T1 and T2 were not consistent across conditions (Figure 5.5). Participants in the physical condition had the highest initial mean scores, but their scores dropped dramatically after two weeks and dropped again after 4-weeks such that participants in this condition had the lowest mean design score (65.02) of the three conditions at the end of the retention period. The design scores for the participants in the 2D condition dropped from T0-T1 and then again less steeply from T1-T2. These participants had the highest mean design score (78.08) at the end of the four weeks. Participants in the 3D condition had the lowest mean design score at T0, but their mean score did not decrease significantly from T0-T1. However, their scores then dropped by 13 points to an average of 69.92 at the end of the four weeks. This is an interesting moderation effect as it was not anticipated that the fidelity would influence any of the cognitive outcomes because the instruction content was controlled (Clark, 1994).

If learning in the simulated environments indeed helped participants with their conceptual understanding, it seems that these effects should have also impacted their initial design score, but this was not the case. One potential explanation for why the 2D and 3D environments supported retention is that participants in these environments engaged in additional practice that helped them retain the information. In the second study, participants described using visualization and mental rehearsal prior to constructing their circuits (Alfred et al., 2016). Research has found that mental practice is an effective way to improve performance, particularly for cognitive tasks (Driskell & Moran, 1994). These beneficial effects also include retention, although they decline over time as well.

While participants in the physical condition constructed their circuit faster at T0, the influence of fidelity on construction time declined. Fidelity was not a significant predictor of construction time across measurement occasions; only cognitive ability. This result may be related to both retention and far transfer. To be able to construct the circuit correctly, participants needed to remember the basics of circuit construction – how the breadboard and components work and how to choose the appropriate resistor. Participants also needed to be able to apply Ohm’s law to different types of circuit connections – series, parallel, and combination. Participants with high cognitive ability were able to do this faster because they retained more of the information related to circuit construction or were better able to apply what they had learned to build a new circuit while participants with low cognitive ability may have had to remind themselves of this information through trial and error.

In general, once participants understood how to construct the circuit they were able to continue to do so with minimal errors in spite of the condition in which they originally learned. Following T0, only six participants made major errors in their construction during T1. Of the six participants, three were in the 3D condition, two were in the 2D condition, and one was in the physical condition. Only three of those participants again made major errors in their circuits in T2, one participant from each condition, and only learning goal orientation was a significant predictor of constructing circuits without errors over the retention period. In this study, LGO was not a significant predictor of any of the other learning outcomes. Prior research has found, however, that an orientation towards learning goals helps with construction because it encourages learners to acquire the knowledge and skills required for competency. An LGO also fosters a desire to explore relationships in greater depth and helps participants build their self-efficacy (Kozlowski et al., 2001).

Limitations

There are several limitations associated with this study. First, because participants had to achieve a minimum level of proficiency for the retention analysis, the sample size was reduced from 70 to 40, and as a result, the power of the analysis was not ideal. The number of participants in each condition was unequal, meaning the design was also unbalanced. Due to a higher dropout rate in the 3D environment, the last 10 participants had a higher probability of being in the 3D condition as more participants were needed for the retention analysis. The proficiency requirement reduced the variation in the sample to include participants who performed higher; thus, the data for the retention analysis at T0 were positively skewed. In addition, the majority of the participants were freshmen and sophomores so this potentially limits the generalizability of the results.

Although efforts were made to address various issues with the simulation software through revisions to the instructional design, there were still characteristics of both the 2D and 3D simulations that may have been detrimental to participants' performance. For example, neither the 2D nor 3D environment incorporated a battery holster; as a result, participants had to figure out how to connect the holster during the construction task, a situation that probably increased their construction time and may have resulted in issues with their circuit if they did not align the positive and negative terminals of the holster correctly. Additionally, the 3D environment had a dual view with the completed schematic on one tab and the breadboard on the other tab and it allowed participants to verify that their circuit components were connected correctly using feedback provided on the schematic view. This feature was not present in the 2D environment as both the 3D and the 2D software were purchased off the shelf.

At T1, 13 participants did not complete the retention survey, and 10 did not complete the retention survey at T2. As a result, the researcher was unaware if they continued to study circuits outside of the research environment, potentially impacting the retention results. However, the overall trends and findings from the retention analysis are consistent with the existing literature on retention and skill decay.

Conclusions

Supporting the findings of Arthur et al. (1998), this study found a greater level of decay in the outcomes evaluated cognitively than those evaluated behaviorally. Although the majority of participants could construct the circuit correctly, they exhibited less proficiency in designing their circuit and performing the requisite calculations for their circuit diagram at T2. This conclusion was reflected in the learning outcomes assessed. Participants’ posttest scores and design scores decreased over time while their construction time and circuit construction remained relatively stable. Learner characteristics seemed to have more influence when in the evaluation of the retention outcomes while the effects of the fidelity, as a main effect, became insignificant for most of the learning outcomes. The interaction between fidelity and measurement occasion for the design scores suggests that fidelity may also influence participants’ conceptual understanding. Participants in the simulated environments had higher design scores at the end of the retention period.

Chapter Summary

This chapter addressed the third aim of this research by exploring how the physical fidelity of the instructional environment impacted retention outcomes and how this relationship was influenced by cognitive ability and learning goal orientation. First, the analysis focused on the cross-sectional outcomes to understand the effects of the IVs immediately after instruction; subsequently, it focused on changes in these outcomes over a 4-week period. The analysis found the fidelity of the learning environment affected circuit construction and construction time post instruction (T0) but not during the retention period. Cognitive ability significantly predicted construction time post instruction and during the retention period while LGO only influenced circuit construction over time. Posttest scores and design scores both decreased significantly during the retention period. This analysis also provided evidence that improvements in the instructional design can yield significant improvements in the learning outcomes for participants learning in simulated environments.

CHAPTER SIX

CONCLUSIONS, BROADER IMPACTS, AND FUTURE RESEARCH

The three primary aims of this research were to identify how the physical fidelity of the learning environment impacted instructional (learning and retention) and transfer outcomes and whether these relationships were influenced by learner characteristics. This research also explored how the transition from the simulated environment to the physical one affected participants' construction process for an electrical circuit and the learning outcomes they achieved. The first study addressed Aim 1, the second Aim 2, and the third Aim 3 as seen in Figure 6.1 below.

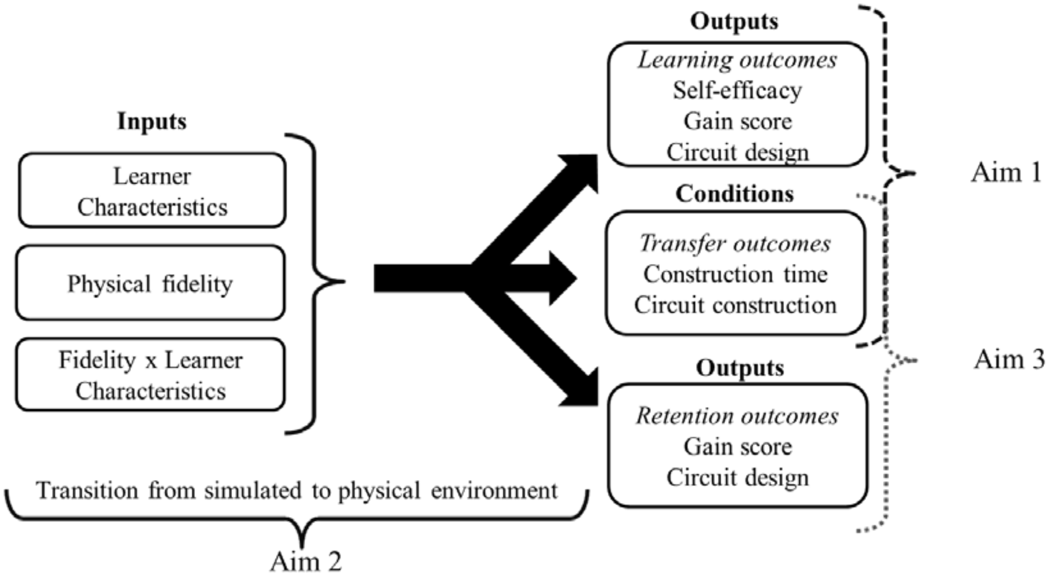


Figure 6.1. Research aims

Overall discussion

The analysis of the results from the first study found that the physical fidelity of the learning environment impacted the affective (self-efficacy) and skill-based learning outcomes (construction and construction time) for participants learning to construct a simple circuit on a breadboard. More specifically, participants learning in the physical environment had a higher self-efficacy and shorter construction time, and were more likely to construct their circuit without errors than participants in the simulated environments. Although these findings suggest learning using the physical components was superior, the study also found evidence of transfer for participants who learned using the 2D and 3D simulations. Approximately 41% of participants (12 of 29) in the simulated environments who attempted construction were able to effectively transition into the physical workspace despite differences in the environments and issues with the instructional design. While the fidelity influenced the affective and skill-based outcomes, learner characteristics impacted the cognitive outcomes (gain score and design score). Cognitive ability was a significant factor for both outcomes, and an interaction effect was also found between fidelity and LGO for construction time, suggesting that evaluating learner characteristics may help improve results when selecting the learning environment.

The analysis of the results from the second study found that the physical fidelity of the learning environment impacted the participants' affect, strategies, and tactics concerning the circuit construction process. Participants experienced some level of isolation, intimidation or pressure when they transitioned from the 2D and 3D conditions to the physical environment. Although most participants using the simulations enjoyed practicing in those conditions, learning to construct a circuit in those conditions was associated with knowledge gaps, inability to identify and troubleshoot issues, and increased levels of negative affect that hurt performance. Some participants suggested that simulations are best used as a supplement to help conceptual understanding.

However, the limitations of the environment were created by the software, not innate features of simulated learning, meaning that both the 2D and 3D simulations can facilitate the transition with minor changes in the design. In addition, these environments can also facilitate transfer by helping participants understand differences they may encounter in the physical environment. However, the transition to the physical environment should not be in a test environment as it can create unnecessary stress and anxiety as found in the second study. These negative emotions, in turn, incurred cognitive resources that potentially detracted from performance (Valiente et al., 2012).

The analysis of the results from the third study demonstrated that while the fidelity of the learning environment impacted construction and construction time initially, the differences decreased over time. The retention analysis indicated no significant main effects for fidelity only an interaction effect with measurement occasion for the design score, suggesting that once the participants became proficient at constructing the circuit, the original learning environment was no longer relevant. However, the interaction effect suggests that the learning environment may continue to influence cognitive outcomes. Learner characteristics, specifically cognitive ability, were found to be a significant predictor of both learning (design score) and retention (posttest score, construction time) outcomes. More specifically, learning goal orientation (LGO) predicted circuit construction, and the measurement occasion was a significant factor in the participants' posttest scores and design scores. Although the majority of participants could construct the circuit correctly, they exhibited less proficiency in designing their circuits and performing the requisite calculations for their circuit diagram. Posttest scores exhibited the behavior of a typical decay curve, a rapid decline initially followed by a less steep one over time (Arthur et al., 1998).

Design scores decreased overall, but the rate of decline was different across the three conditions. The interaction between fidelity and measurement occasion for design score suggested that fidelity may also influence participants' conceptual understanding. Early research on computer-based learning environments found evidence supporting that these environments can be used as "cognitive tools for learning" (Lajoie 1993, p. 285). Because the simulations used in the study did not offer some of the typical advantages of simulations such as displaying invisible phenomena and increased interactivity, it was hypothesized that the mental rehearsal and visualization used by participants who learned in this environment supported retention of the concepts related to circuit design (Alfred et al., 2016). Construction time was not significantly different across measurement occasions, and circuit construction was also fairly consistent, these findings from the retention analysis supporting Arthur et al. (1998), who found that cognitive outcomes decay more rapidly than physical ones and that outcomes assessed cognitively will demonstrate more decay than those assessed behaviorally.

The analysis of the first experiment found in Chapter 3 and the second in Chapter 5 found both consistent and conflicting results. Unlike in the first experiment, fidelity was not found a significant predictor of self-efficacy (SE) in experiment two. While participants in the physical and 3D conditions had similar SE in the studies, participants in the 2D condition had a much higher post instruction SE (Figure 6.2) in the second study. These differences were potentially attributable to improvements in the instructional design - specifically providing the 2D participants with transition notes and allowing them to practice reading resistors – that helped them to feel more confident in their ability to work with circuits. These differences in SE may also be attributable to differences in the participant profiles. Although the gender ratio was comparable and most participants in both studies had little to no prior experience working with circuits, the second experiment involved a younger predominantly undergraduate participant population, their age potentially influencing their experience and comfort working in simulated environments.

In the first study, both cognitive ability and pretest scores impacted gain scores, with the latter having the higher unique effect size. In the second experiment, only pretest scores were a significant predictor of gain score (Table 5.1). Another change made in the second experiment was to include 2-3 practice exercises after each video lecture. Having participants complete these activities helped make them active learners (Prince, 2004). This change may also have offset the gains attributable to cognitive ability. For both studies, cognitive ability was also the only significant predictor of design score, a result that was expected as both studies used the same construction activity. In both participants with a high cognitive ability were better able to design the specified circuit than those with a lower one.

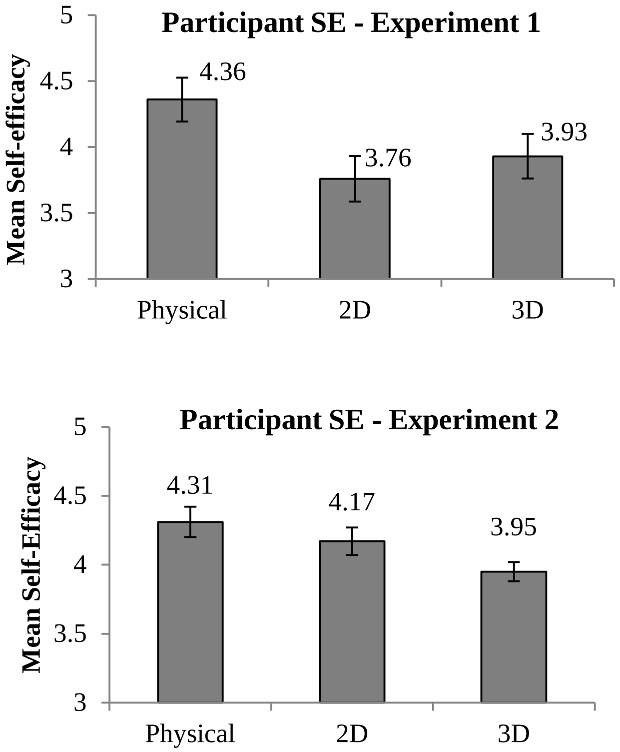


Figure 6.2. Comparison of mean SE by condition between experiment 1 and 2

Table 6.1. Comparison of mean construction time per condition

	Experiment 1				**Experiment 2**		
Condition	Mean	N	Std. Deviation		Mean	N	Std. Deviation
Physical	15.47	15	12.39		15.18	22	6.51
2D	29.88	16	14.76		23.19	21	9.98
3D	30.43	13	16.91		20.59	22	11.97

In addition, consistent with the first study, the second experiment also found that fidelity was a significant predictor of construction time and correct circuit construction. In the first experiment, the participants in the physical condition constructed their circuits in half the time as those in the 2D and 3D environments (Table 6.1). In experiment two, the construction time among the participants was closer in range, with only participants in the 2D condition constructing their circuit significantly slower than those in the physical condition. However, overall, the participants in experiment two constructed their circuits faster than those in the first study. These differences in construction time were, in part, due to the fact that participants in the simulated environment in experiment one spent several minutes trying to determine the resistance of the through-hole resistors (Alfred, Lee, Neyens, & Gramopadhye, under review). Video data analysis also found that participants in the physical condition took a more methodical approach to circuit construction while participants in the 2D and 3D conditions employed a trial-and-error approach, which resulted in a higher mean construction time for these participants.

The video lecture for the first study showed participants how to read a resistor and included an embedded practice activity. In experiment two, all participants saw this demonstration and took part in a practice activity in which they were required to find the value of physical through-hole resistors. This was one form of scaffolding that was incorporated into the experiment two to facilitate transfer for participants learning in the simulated environments. This change probably reduced the construction time for participants in the simulated environments. In the first study, LGO also moderated the relationship between fidelity and construction time. This effect, however, was not found in experiment two.

The two experiments also found differences in circuit construction among the participants in the three conditions. As previously mentioned, the initial construction task was the same for both experiments. In experiment two, participants in the 2D condition had higher odds of constructing their circuit without errors. This finding may be related to their longer construction time. They may have simply spent more time working to ensure their circuit was correct. The first experiment did not find significant differences in the odds of constructing a circuit without error for participants in the physical (11) and 2D conditions (8). Participants in the 3D condition, however, had lower odds, .064 times [95% CI: .003, .617], than participants in the physical condition. In the second experiment, these participants constructed their circuits without error at a comparable rate to participants in the physical condition and at a time that was not significantly different. However, in both experiments, only participants in the 3D condition dropped out or were withdrawn because they could not complete the practice activities – 3 in experiment one and 4 in experiment two. Some participants struggled to work in the 3D environment. The environment may have added an extraneous load, explaining why it would have been detrimental to learning and why some participants could not establish proficiency (Paas & Sweller, 2014). In the first experiment, the participants who dropped had very little experience working with circuits but at least a little experience working in 3D environments. In the second experiment, all the participants who dropped had no experience working with circuits, and three reported having no experience working in 3D environments, with the fourth having very little. Prior research has found that the increased complexity of 3D environments may make it difficult for students to interact with it and beginners in particular may struggle to comprehend all the information being conveyed (Stuerzlinger & Wingrave, 2011; Gillet et al., 2013).

Conclusions

This research found that fidelity impacted skill-based learning outcomes while the learner characteristics, particularly cognitive ability, impacted both cognitive and skill-based learning outcomes. The improvements in the performance of participants in the second study demonstrated that instructional design is particularly important for participants learning in simulated learning environments. In addition to good instructional design, simulated learning environments should account for individual differences and try to minimize the cognitive load for learners when they transition to the real-world environment. This may be particularly important for participants who do not have as much experience or exposure to simulated environments. Over time, the effect of fidelity faded, but cognitive ability remained a significant predictor. This finding suggested that once participants understood how to construct a circuit, the condition they originally learned in was no longer a factor in their circuit construction and time. However, learning in the 2D or 3D simulations potentially helped students develop a stronger conceptual understanding that supported retention.

Another finding from this analysis was that learning to construct a circuit in a 3D environment offered no advantage over the 2D simulation. Constructing a circuit is primarily a 2D task, so working in a 3D environment may add no value and this may be the case for 2D tasks in general. Participants in these two conditions were comparable in terms of affective (self-efficacy) and skill-based outcomes (construction time). However, participants in the 2D environment had higher odds of constructing their circuit correctly in both experiments than those who learned in the 3D environment. Also, 2D environments are typically less expensive to develop and maintain and can operate on less powerful computers.

Based on the results, some acclimation to the physical environment would be beneficial for learners using a simulated environment. The second experiment found that improvements in the instructional design led to improved learning and transfer outcomes for participants who learned in these environments. However, further enhancements in both the 2D and 3D simulations could further facilitate the transition. In general, because simulated environments represent an abstraction of reality, designers have to decide which simplifications a simulation should employ to support learning outcomes without negatively impacting transfer and retention. For example, both the 2D and 3D environments should force learners to practice reading resistors from a resistance calculation sheet as opposed to typing in the value and the 2D condition could allow learners to orient the breadboard horizontally or vertically depending on their preference. Additionally, learners should be allowed to operate in the physical environment without the immediate pressure of performance as doing so could potentially ease the anxiety and pressure participants described in the second study.

Despite learners' having to make some adjustments, simulated laboratories have several practical benefits over physical laboratories. Simulated laboratories can be offered in an online setting and do not require the equipment and facilities needed for physical laboratories. The maintenance costs for these environments may also be lower than physical laboratories. Further, learners have increased access as instructors and/or teaching assistants do not need to be present. Finally, simulated environments can address the safety concern as well as cost, two factors which may limit the students’ ability to experiment and explore using the physical tools and equipment.

Broader Impacts and Research Contributions

Non-traditional students wanting a technical degree may be constrained to course offerings at their nearest educational institution because few institutions currently offer technical curricula in online settings. The results of this research have implications for the design and implementation of simulations in instructional settings, particularly for technical tasks. The findings provide insights about how tasks can be taught effectively in simulated environments as well as information about how the physical fidelity of the learning environment impacts learning outcomes. In the first study, participants who learned to construct the circuit using the physical components achieved better results than those who learned in either the 2D or 3D simulation. With a few minor modifications in the instructional content, the third study found comparable results between participants in the 2D simulation and the physical conditions, while participants in the 3D simulation, although improved, still demonstrated the lowest level of proficiency. These findings have important implications for access to educational opportunities. In addition to increasing the number and range of courses that can be taught in an online setting, it can potentially attract and retain student populations – older, minority, full-time workers- with high dropout rates (Hirschy et al., 2011). These students are likely to enroll in online courses. This setting can also help provide educational opportunities to students, such as those living in rural areas, who also have limited access to different programs due to their geographic locations. With the push for free community college gaining traction around the country and with states such as Tennessee and Oregon already offering this option, well-designed simulated learning environments represent an opportunity to support engineering and technical education in this climate. Additionally, simulated labs can provide learning opportunities to students in impoverished school districts that cannot fund the labs and required materials or offer online courses for their students.

This research also has implications for personalized education. Advanced personalized education has been identified as one of the grand engineering challenges developed by the National Academy of Engineering ("NAE Grand Challenges for Engineering," 2016). In addition to identifying the impact of physical fidelity on learning outcomes, this research also sought to understand how specific learner characteristics interacted with the relationship between physical fidelity and learning outcomes. As technology continues to become more prominent in education, it will become increasingly more important to understand not just whether it is effective but for what tasks and for which individuals it is most effective. This research begins to answer these questions by providing evidence about how the cognitive ability and goal orientation of the learner impacted the effectiveness of the learning in simulated environments.

Directions for future work

While most previous research conducted on simulated learning environments has concentrated on conceptual learning, this research focused on the use of simulated environments to develop technical skills. However, it is just a first step, with several key areas requiring future study. First, future research should continue to investigate the use of simulated environments for technical tasks, evaluating whether the findings from this study are consistent across different tasks**.** The nature of the task probably influences its ability to be learned effectively in an online environment. For example, hands-on tasks, such as welding, with a strong motor component could result in different transfer outcomes. Secondly, because the relationship between the physical fidelity of the learning environment and transfer may be dependent on the specific characteristics of the learner, such as current skill level (Alexander et al., 2005), it is also important to continue to investigate the relative importance of these characteristics. In addition, because the appropriate level of fidelity may change depending on specific task characteristics or the learner's progress, researchers should investigate varying the level of fidelity to determine its influences on instructional and transfer outcomes at different stages in the learning process.

One of the unanticipated findings from the analysis concerned the emotional transition participants faced when moving from the simulated environments to the real-world environment. The research found that participants learning in the simulated environments experienced feelings of isolation and anxiety when they transitioned to working with physical components. Although self-efficacy was measured following instruction, it appeared that self-efficacy evolved during the construction process with some learners losing confidence in their ability to construct the circuit. In addition to identifying the appropriate level of fidelity required to achieve the desired level of proficiency and skill transfer in learners, instructors and designers also have to consider the emotional transition learners must manage as they transition from the simulated environments to the physical environment. For the research task, how they managed these emotions was less crucial for their success, but for critical tasks it will be very important to help learners manage their emotions and maintain their self-efficacy through this transition. Future work should examine the affect of students as they learn a skill in a simulated environment and how their emotions evolve as they attempt to transfer skills learned in simulated environments to real-world applications.

APPENDICES

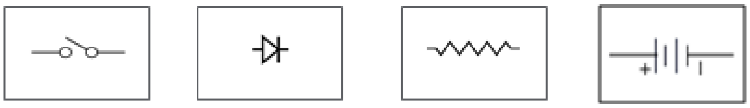
Appendix A

Pretest for experiment one and experiment two

Pre-test

Participant ID______________________

Figure 1


1 2 3 4

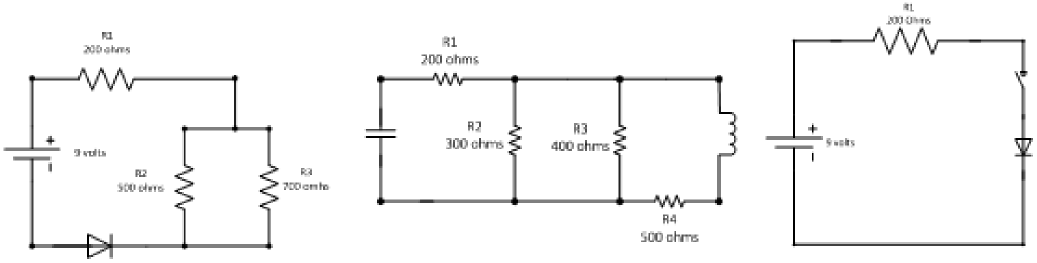
1) Match the electrical component with its correct symbol from figure 1

- a) 1 = Switch, 2 = Capacitor, 3 = Resistor, 4 = Inductor
- b) 1 = Capacitor, 2 = Battery, 3 = Inductor, 4 = Switch
- c) 1= Battery, 2 = Diode, 3 = Inductor, 4 = Capacitor
- d) 1 = Switch, 2 = Diode, 3 = Resistor, 4 = Battery

2) _______is opposition to flow due to friction and _______ is the movement of electrons in an electrical circuit.

- a. Voltage; current
- b. Current; voltage
- c. Resistance; current
- d. Resistance; voltage

Figure 2

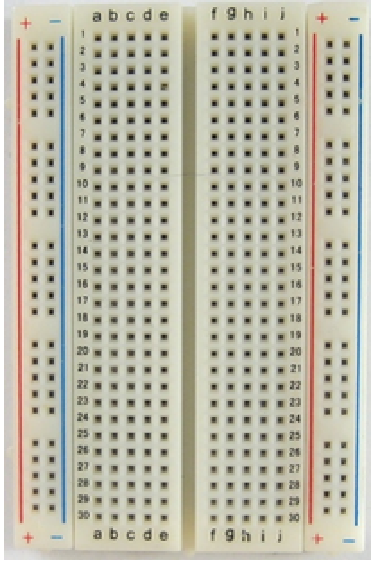


A B C

3) Which of the diagrams in figure 4 represents a circuit producing a continuous current flow?

- a) A
- b) B
- c) C
- d) A & B

Figure 3



4) What of the following statements about how a breadboard (figure 3) functions is true?

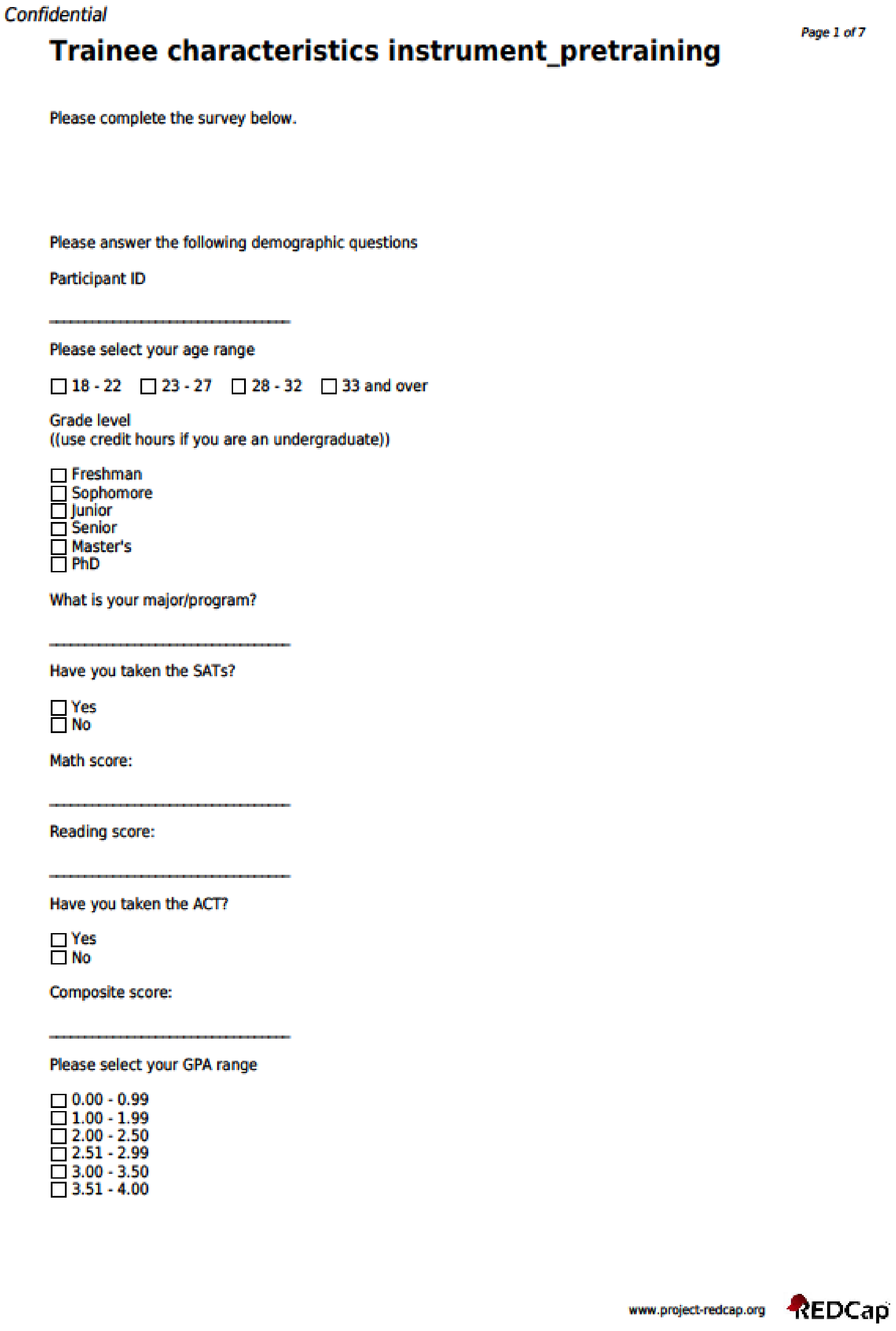
a) Columns (a-j) are connected except across the gap in the middle
b) Rows (1-30) are connected except the positive (red) and negative (blue) strips
c) The positive (red) and negative (blue) strips are connected in groups of five
d) All of the statements are true

5) Two LEDs are connected in series. The forward voltage of each LED is 2.3 volts and the maximum continuous current for each LED is 18mA. Find the minimum resistance needed to prevent each LED from being blown if a 9 volt battery is used to construct the circuit.

a) 500 ohms
b) 183.33 ohms
c) 372.22 ohms
d) 244.44 ohms

Appendix B

Demographic survey



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Page 1 of 7

Trainee characteristics instrument_pretraining

Please complete the survey below.

Please answer the following demographic questions

Participant ID

____

Please select your age range

☐ 18 - 22 ☐ 23 - 27 ☐ 28 - 32 ☐ 33 and over

Grade level
((use credit hours if you are an undergraduate))

☐ Freshman
☐ Sophomore
☐ Junior
☐ Senior
☐ Master's
☐ PhD

What is your major/program?

____

Have you taken the SATs?

☐ Yes
☐ No

Math score:

____

Reading score:

____

Have you taken the ACT?

☐ Yes
☐ No

Composite score:

____

Please select your GPA range

☐ 0.00 - 0.99
☐ 1.00 - 1.99
☐ 2.00 - 2.50
☐ 2.51 - 2.99
☐ 3.00 - 3.50
☐ 3.51 - 4.00

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How much experience do you have operating in a 3D environment (such as playing video games)?

☐ No experience ☐ Very little experience ☐ Some experience ☐ A lot of experience

Have you completed any electrical circuits course (such as ECE 202, ECE 262 or ECE 307)?

☐ No
☐ Yes

When did you complete the course?

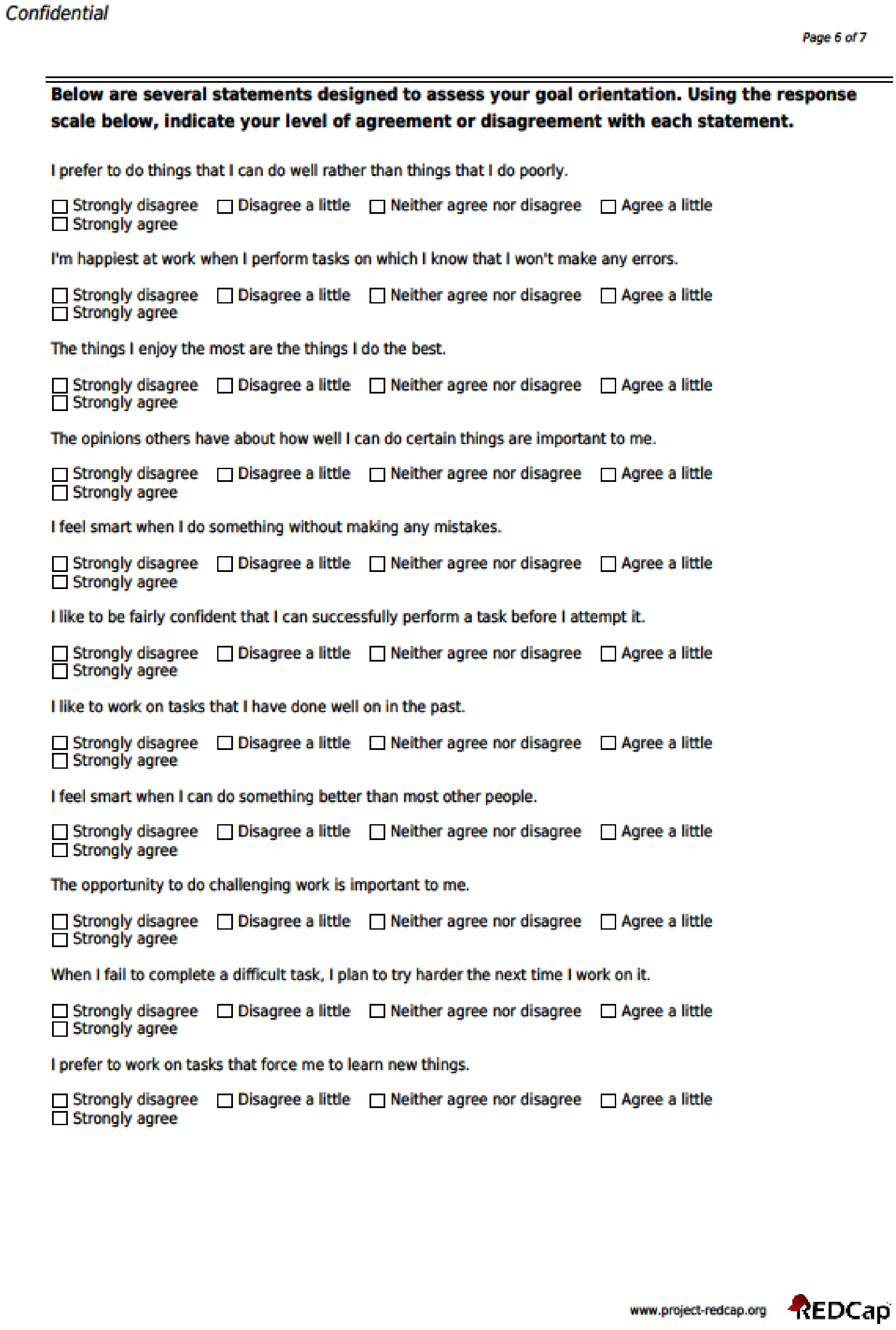
☐ Current academic year (2015 - 2016)
☐ Previous academic year (2014 - 2015)
☐ Two years ago (2013 - 2014)
☐ Three years ago (2012 - 2013)
☐ More than three years ago (before 2012 school year)

How much experience do you have working with electrical circuits?

☐ No experience ☐ Very little experience ☐ Some experience ☐ A lot of experience

Appendix C

Goal Orientation Survey



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Page 6 of 7

Below are several statements designed to assess your goal orientation. Using the response scale below, indicate your level of agreement or disagreement with each statement.

I prefer to do things that I can do well rather than things that I do poorly.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I'm happiest at work when I perform tasks on which I know that I won't make any errors.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

The things I enjoy the most are the things I do the best.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

The opinions others have about how well I can do certain things are important to me.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I feel smart when I do something without making any mistakes.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I like to be fairly confident that I can successfully perform a task before I attempt it.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I like to work on tasks that I have done well on in the past.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I feel smart when I can do something better than most other people.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

The opportunity to do challenging work is important to me.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

When I fail to complete a difficult task, I plan to try harder the next time I work on it.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I prefer to work on tasks that force me to learn new things.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

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The opportunity to learn new things is important to me.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I do my best when I'm working on a fairly difficult task.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

I try hard to improve my past performance.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

The opportunity to extend the range of my abilities is important to me.

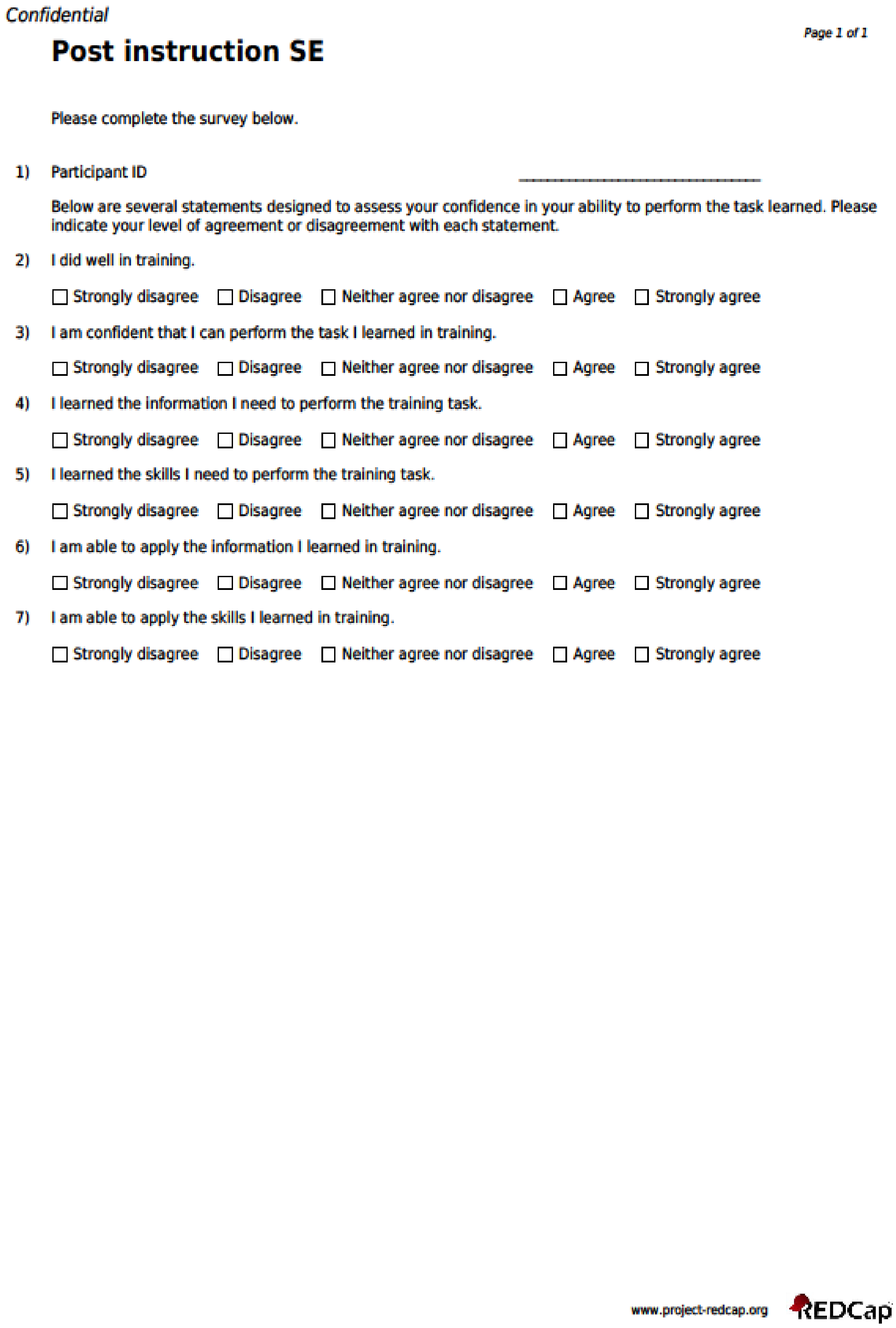
☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

When I have difficulty solving a problem, I enjoy trying different approaches to see which one will work.

☐ Strongly disagree ☐ Disagree a little ☐ Neither agree nor disagree ☐ Agree a little
☐ Strongly agree

Appendix D

Post instruction self-efficacy instrument



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Page 1 of 1

Post instruction SE

Please complete the survey below.

1) Participant ID ________________________________

Below are several statements designed to assess your confidence in your ability to perform the task learned. Please indicate your level of agreement or disagreement with each statement.

2) I did well in training.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

3) I am confident that I can perform the task I learned in training.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

4) I learned the information I need to perform the training task.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

5) I learned the skills I need to perform the training task.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

6) I am able to apply the information I learned in training.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

7) I am able to apply the skills I learned in training.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

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Appendix E

Posttest for experiment one and experiment two (T0)

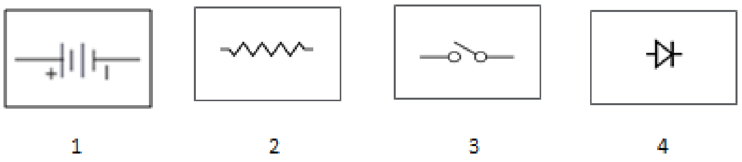
Post-test

Participant ID______________________________

1) _______ is the movement of electrons in an electrical circuit and _________describes the difference in the electrical charge between two points that can push the electrons between two points.

a. Current; voltage
b. Voltage; resistance
c. Resistance; current
d. Voltage; current

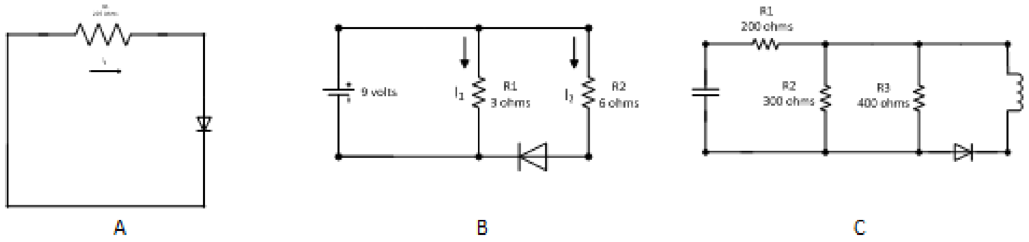
Figure 1



2) Match the electrical component with its correct symbol from figure 1

a) 1 = Inductor 2 = Resistor, 3 = Battery, 4 = Diode
b) 1= Battery, 2 = Resistor, 3 = Switch, 4 = Diode
c) 1 = Capacitor, 2 = Battery, 3 = Inductor, 4 = Switch
d) 1 = Battery, 2 = Diode, 3 = Switch, 4 = Battery

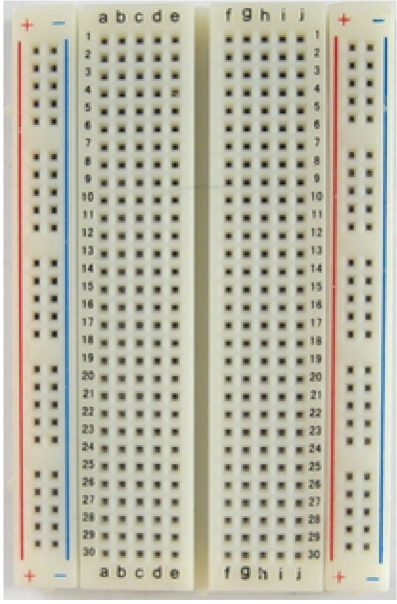
Figure 2



3) Which of the diagrams in figure 2 represents a circuit producing a continuous current flow?

a) A
b) B
c) C
d) A & C

Figure 3



4) What of the following statements about how a breadboard (figure 3) functions is true?

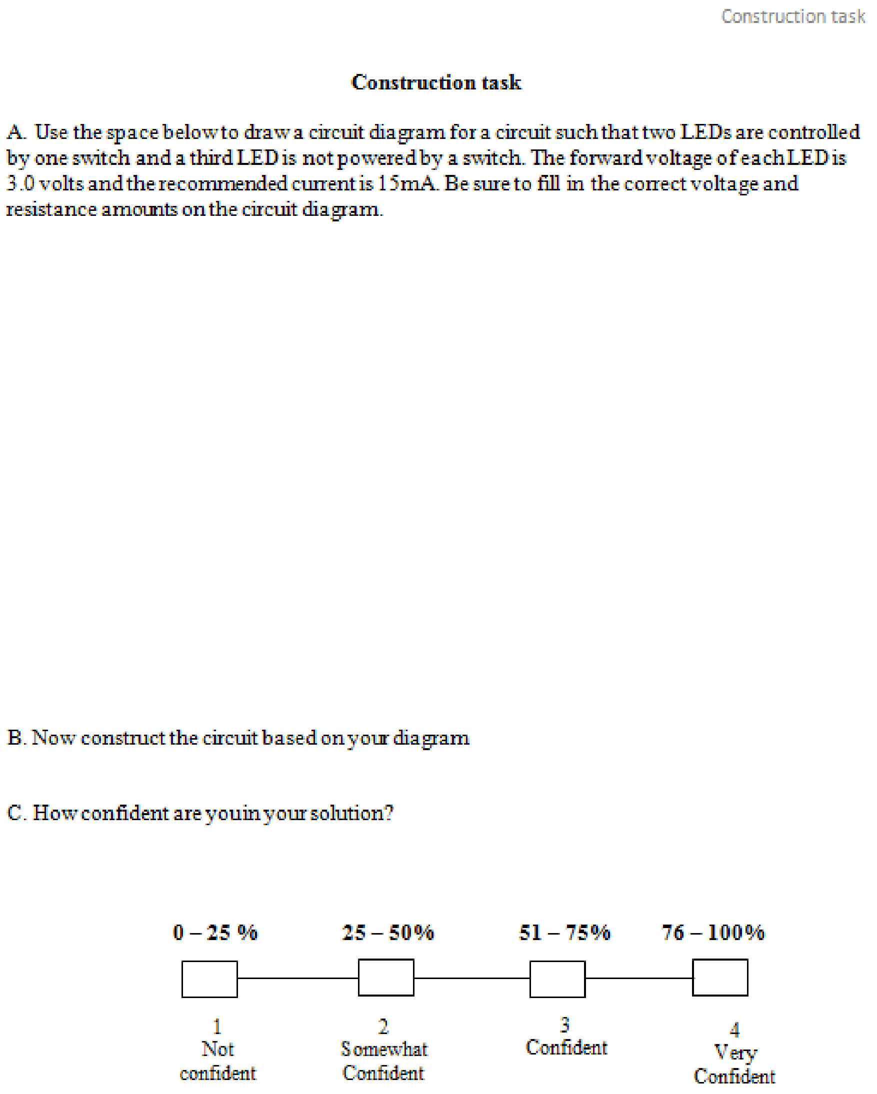
a) Columns (a-j) are connected except across the gap in the middle
b) Rows (1-30) are connected except the positive (red) and negative (blue) strips
c) The positive (red) and negative (blue) strips are connected in groups of five
d) All of the statements are true

5) Two LEDs are connected in parallel. If the forward voltage of each LED is 1.7 volts and the maximum continuous current of each LED is 20mA. Find the minimum resistance needed to prevent each LED from being blown if a 6 volt battery is used to construct the circuit.

a) 130 ohms
b) 154 ohms
c) 215 ohms
d) 300 ohms

Appendix F

Construction task for experiment one and experiment three (T0)



Construction task

Construction task

A. Use the space below to draw a circuit diagram for a circuit such that two LEDs are controlled by one switch and a third LED is not powered by a switch. The forward voltage of each LED is 3.0 volts and the recommended current is 15mA. Be sure to fill in the correct voltage and resistance amounts on the circuit diagram.

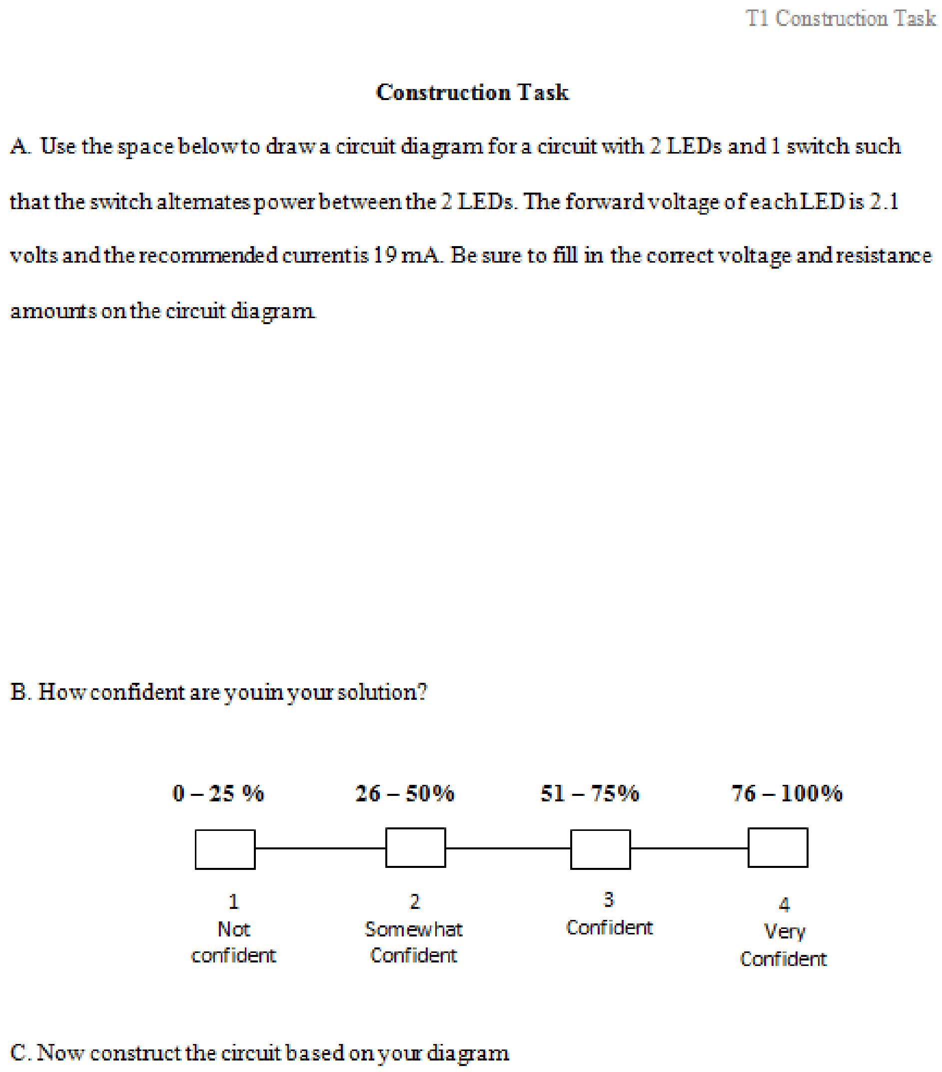
B. Now construct the circuit based on your diagram

C. How confident are you in your solution?

0 – 25 %	**25 – 50%**	**51 – 75%**	**76 – 100%**
☐	☐	☐	☐
1 Not confident	2 Somewhat Confident	3 Confident	4 Very Confident

Appendix G

Construction task (T1)



T1 Construction Task

Construction Task

A. Use the space below to draw a circuit diagram for a circuit with 2 LEDs and 1 switch such that the switch alternates power between the 2 LEDs. The forward voltage of each LED is 2.1 volts and the recommended current is 19 mA. Be sure to fill in the correct voltage and resistance amounts on the circuit diagram.

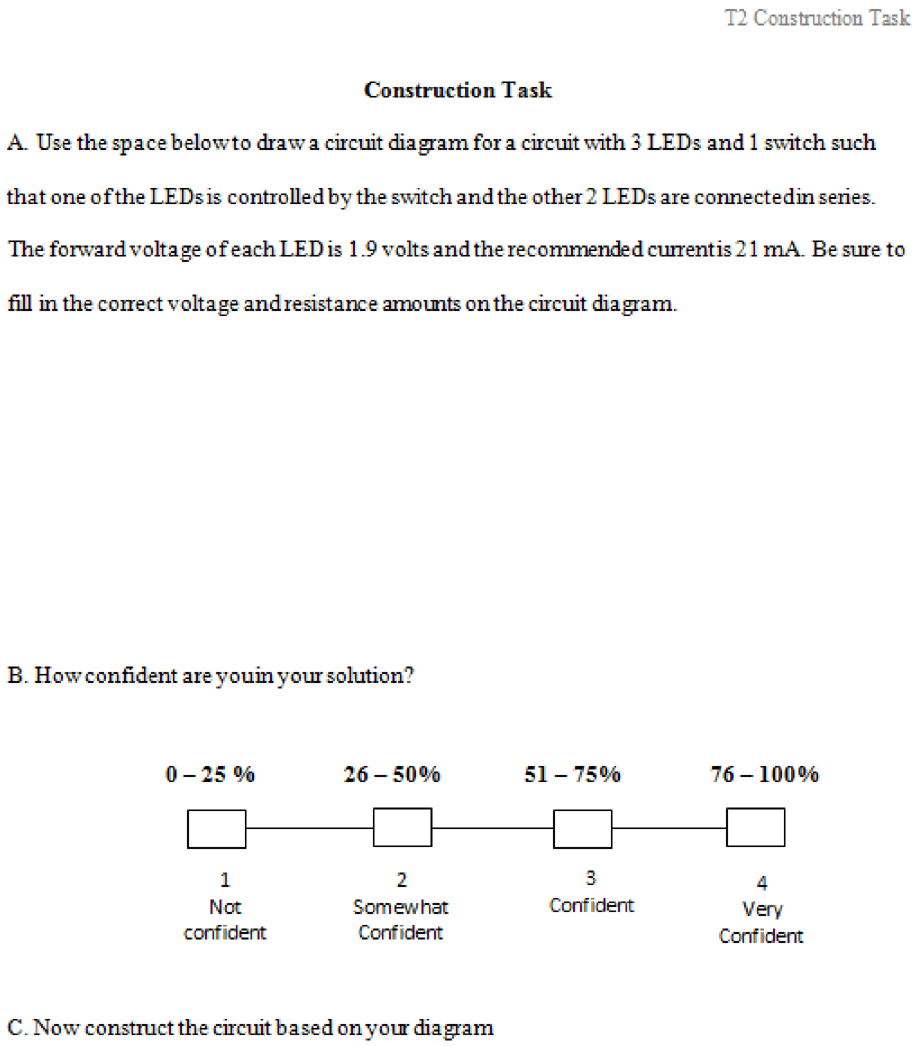
B. How confident are you in your solution?

0 – 25 %	**26 – 50%**	**51 – 75%**	**76 – 100%**
☐	☐	☐	☐
1 Not confident	2 Somewhat Confident	3 Confident	4 Very Confident

C. Now construct the circuit based on your diagram

Appendix H

Construction task (T2)



T2 Construction Task

Construction Task

A. Use the space below to draw a circuit diagram for a circuit with 3 LEDs and 1 switch such that one of the LEDs is controlled by the switch and the other 2 LEDs are connected in series. The forward voltage of each LED is 1.9 volts and the recommended current is 21 mA. Be sure to fill in the correct voltage and resistance amounts on the circuit diagram.

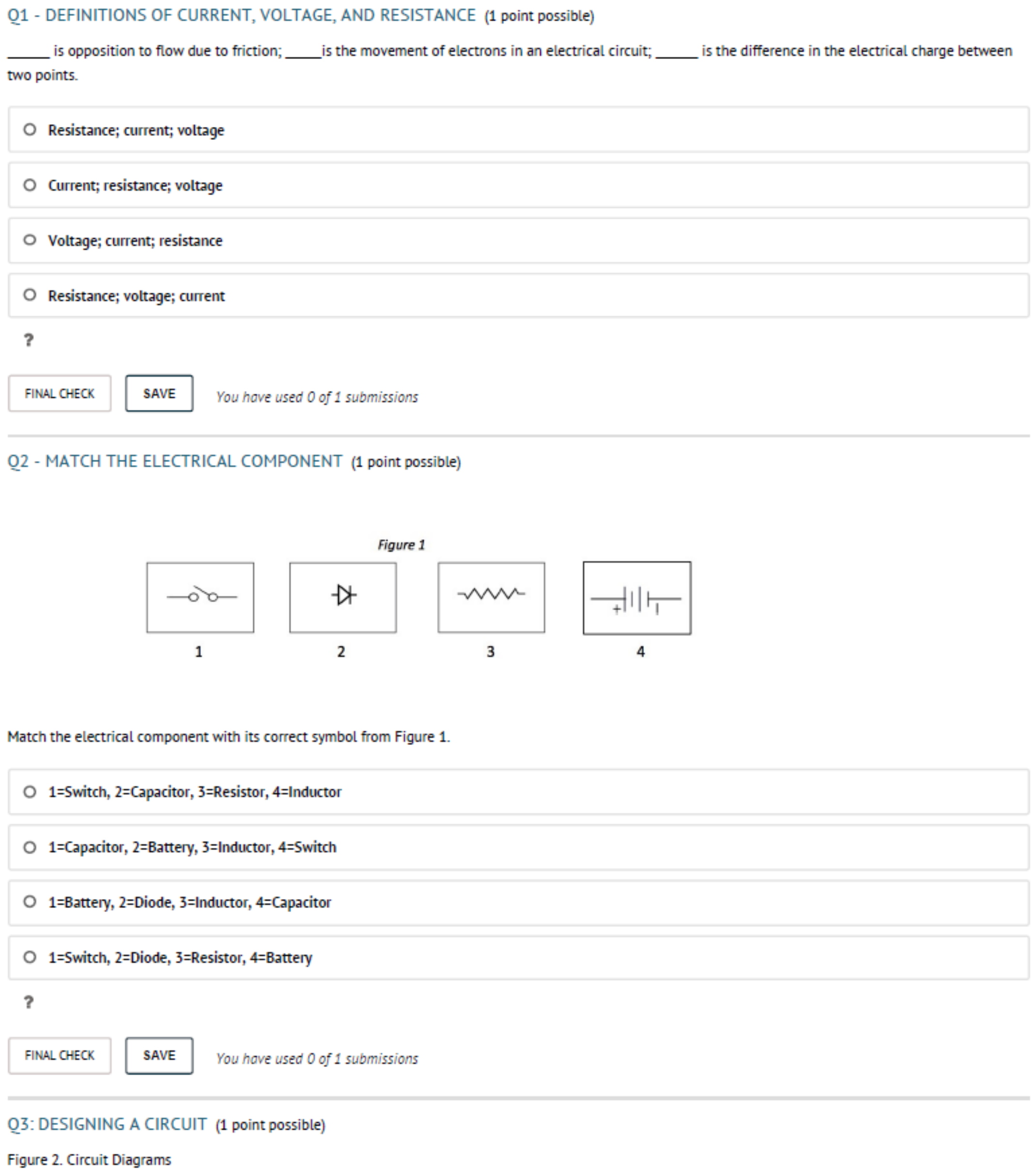
B. How confident are you in your solution?

0 – 25 %	**26 – 50%**	**51 – 75%**	**76 – 100%**
☐	☐	☐	☐
1 Not confident	2 Somewhat Confident	3 Confident	4 Very Confident

C. Now construct the circuit based on your diagram

Appendix I

Posttest (T1)



Q1 - DEFINITIONS OF CURRENT, VOLTAGE, AND RESISTANCE (1 point possible)

______ is opposition to flow due to friction; _____is the movement of electrons in an electrical circuit; ______ is the difference in the electrical charge between two points.

- ○ Resistance; current; voltage
- ○ Current; resistance; voltage
- ○ Voltage; current; resistance
- ○ Resistance; voltage; current

You have used 0 of 1 submissions

Q2 - MATCH THE ELECTRICAL COMPONENT (1 point possible)

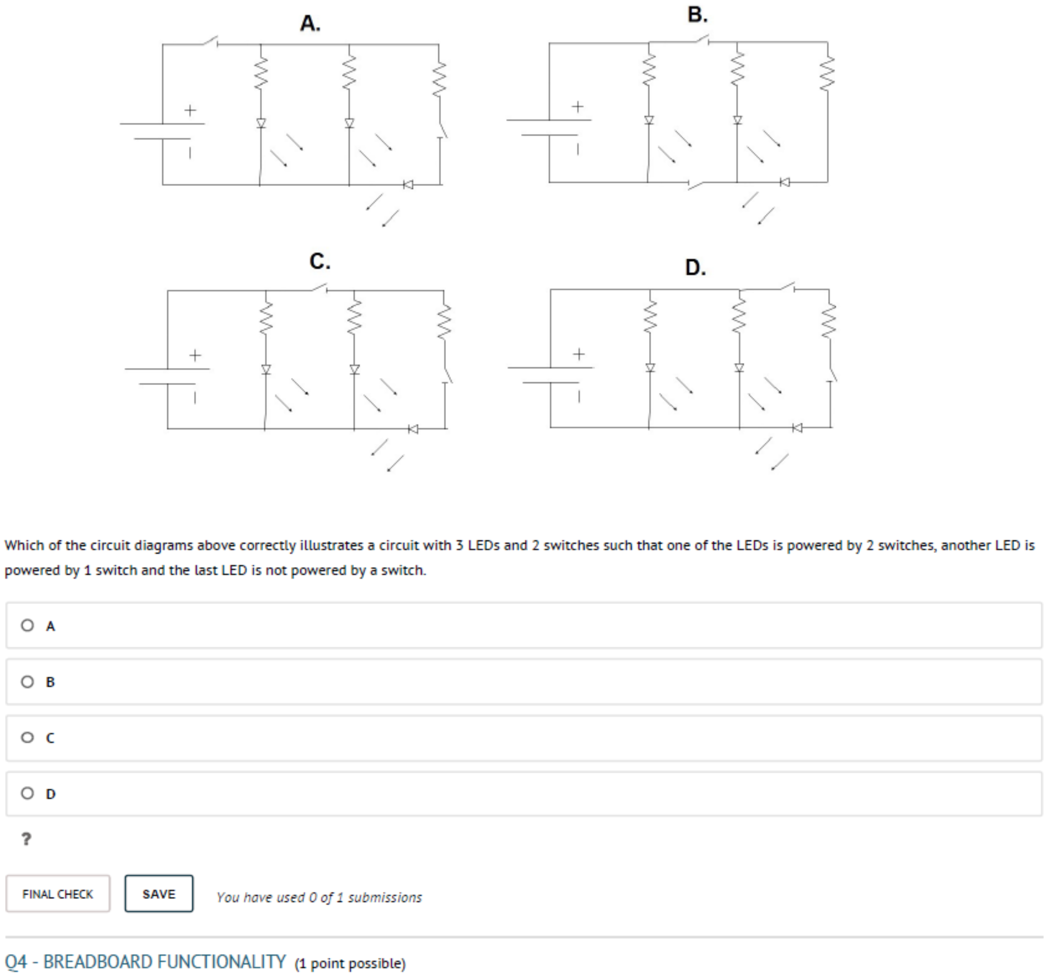
Match the electrical component with its correct symbol from Figure 1.

- ○ 1=Switch, 2=Capacitor, 3=Resistor, 4=Inductor
- ○ 1=Capacitor, 2=Battery, 3=Inductor, 4=Switch
- ○ 1=Battery, 2=Diode, 3=Inductor, 4=Capacitor
- ○ 1=Switch, 2=Diode, 3=Resistor, 4=Battery

You have used 0 of 1 submissions

Q3: DESIGNING A CIRCUIT (1 point possible)

Figure 2. Circuit Diagrams



Which of the circuit diagrams above correctly illustrates a circuit with 3 LEDs and 2 switches such that one of the LEDs is powered by 2 switches, another LED is powered by 1 switch and the last LED is not powered by a switch.

○ A

○ B

○ C

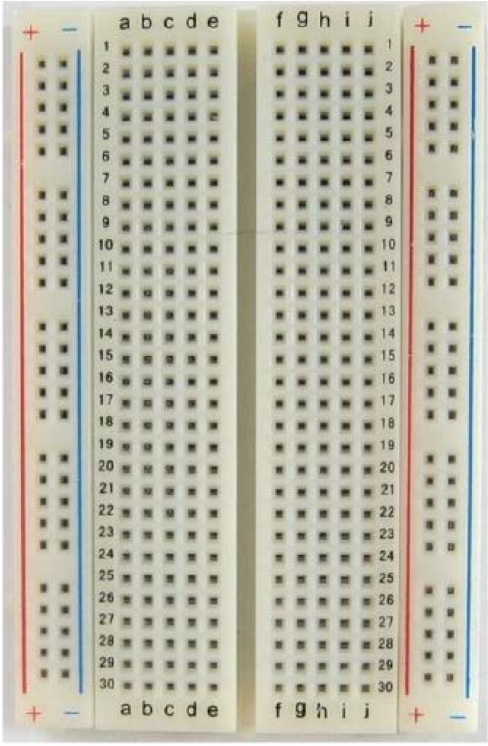
○ D

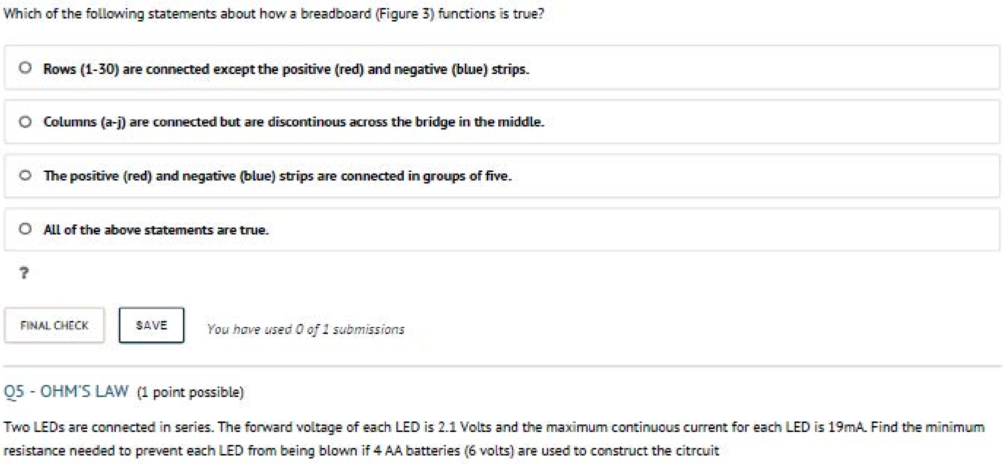
?

You have used 0 of 1 submissions

Q4 - BREADBOARD FUNCTIONALITY (1 point possible)

Figure 3





Which of the following statements about how a breadboard (Figure 3) functions is true?

○ **Rows (1-30) are connected except the positive (red) and negative (blue) strips.**

○ **Columns (a-j) are connected but are discontinous across the bridge in the middle.**

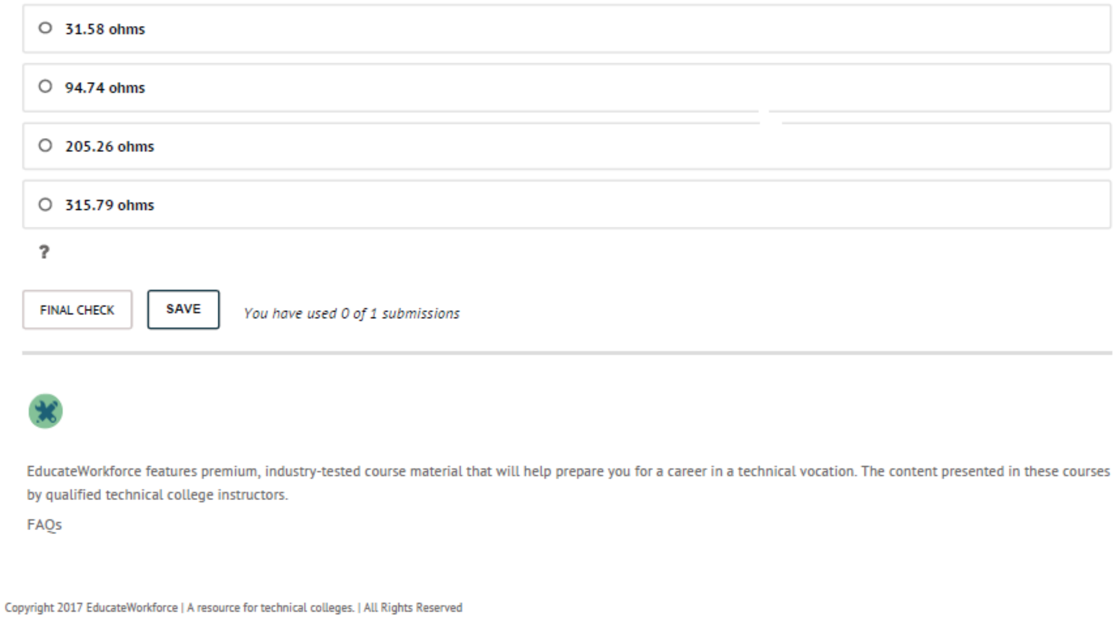
○ **The positive (red) and negative (blue) strips are connected in groups of five.**

○ **All of the above statements are true.**

You have used 0 of 1 submissions

Q5 - OHM'S LAW (1 point possible)

Two LEDs are connected in series. The forward voltage of each LED is 2.1 Volts and the maximum continuous current for each LED is 19mA. Find the minimum resistance needed to prevent each LED from being blown if 4 AA batteries (6 volts) are used to construct the citrcuit



○ 31.58 ohms

○ 94.74 ohms

○ 205.26 ohms

○ 315.79 ohms

You have used 0 of 1 submissions

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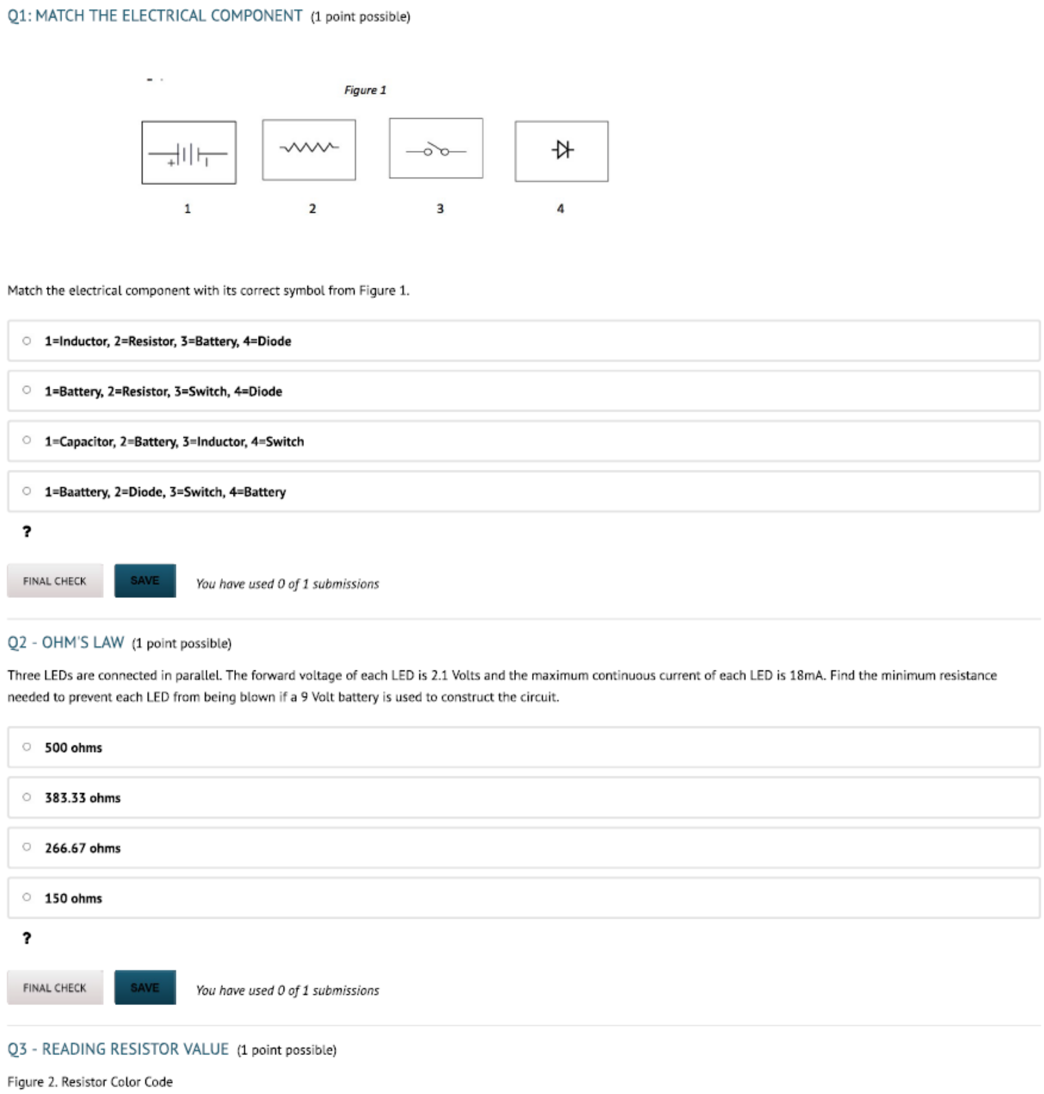
Appendix J

Posttest (T2)



Q1: MATCH THE ELECTRICAL COMPONENT (1 point possible)

Match the electrical component with its correct symbol from Figure 1.

○ **1=Inductor, 2=Resistor, 3=Battery, 4=Diode**

○ **1=Battery, 2=Resistor, 3=Switch, 4=Diode**

○ **1=Capacitor, 2=Battery, 3=Inductor, 4=Switch**

○ **1=Baattery, 2=Diode, 3=Switch, 4=Battery**

?

You have used 0 of 1 submissions

Q2 - OHM'S LAW (1 point possible)

Three LEDs are connected in parallel. The forward voltage of each LED is 2.1 Volts and the maximum continuous current of each LED is 18mA. Find the minimum resistance needed to prevent each LED from being blown if a 9 Volt battery is used to construct the circuit.

○ **500 ohms**

○ **383.33 ohms**

○ **266.67 ohms**

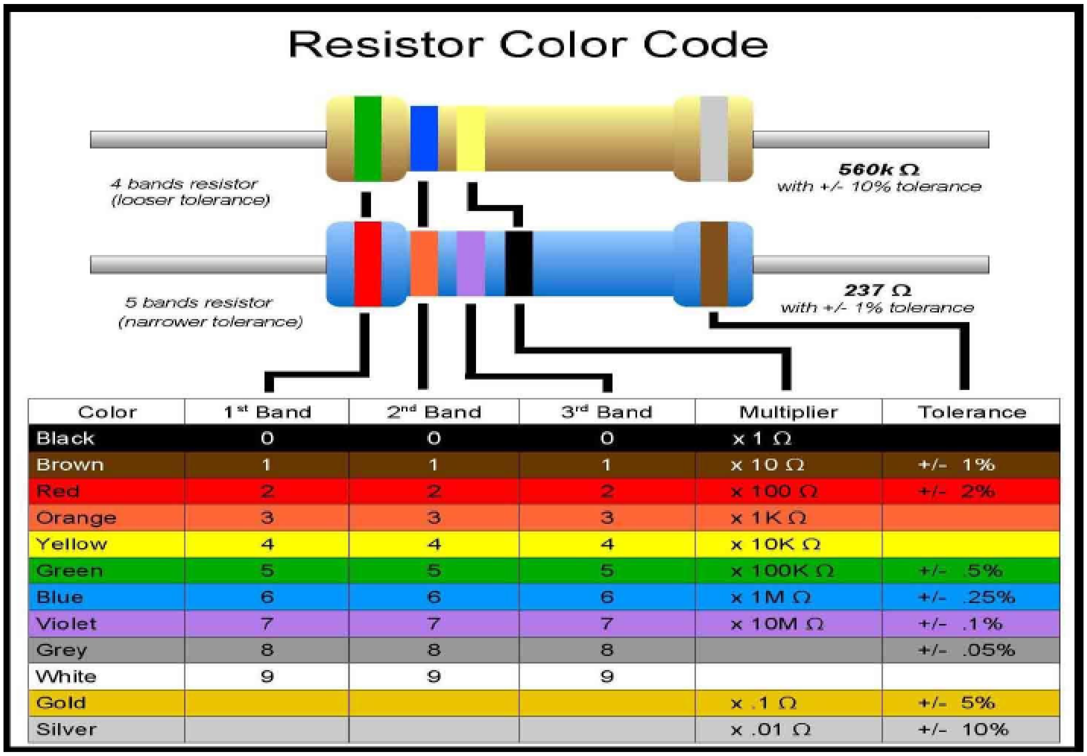
○ **150 ohms**

?

You have used 0 of 1 submissions

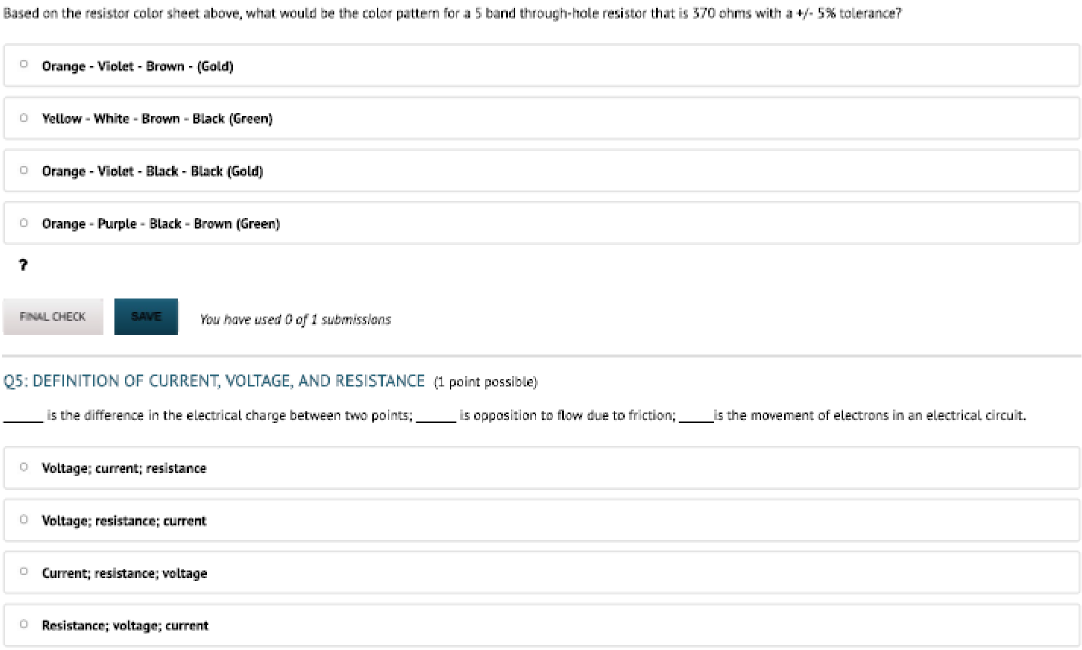
Q3 - READING RESISTOR VALUE (1 point possible)

Figure 2. Resistor Color Code



Resistor Color Code

Color	1st Band	2nd Band	3rd Band	Multiplier	Tolerance
Black	0	0	0	x 1 Ω	
Brown	1	1	1	x 10 Ω	+/- 1%
Red	2	2	2	x 100 Ω	+/- 2%
Orange	3	3	3	x 1K Ω	
Yellow	4	4	4	x 10K Ω	
Green	5	5	5	x 100K Ω	+/- .5%
Blue	6	6	6	x 1M Ω	+/- .25%
Violet	7	7	7	x 10M Ω	+/- .1%
Grey	8	8	8		+/- .05%
White	9	9	9		
Gold				x .1 Ω	+/- 5%
Silver				x .01 Ω	+/- 10%



Based on the resistor color sheet above, what would be the color pattern for a 5 band through-hole resistor that is 370 ohms with a +/- 5% tolerance?

○ **Orange - Violet - Brown - (Gold)**

○ **Yellow - White - Brown - Black (Green)**

○ **Orange - Violet - Black - Black (Gold)**

○ **Orange - Purple - Black - Brown (Green)**

?

You have used 0 of 1 submissions

Q5: DEFINITION OF CURRENT, VOLTAGE, AND RESISTANCE (1 point possible)

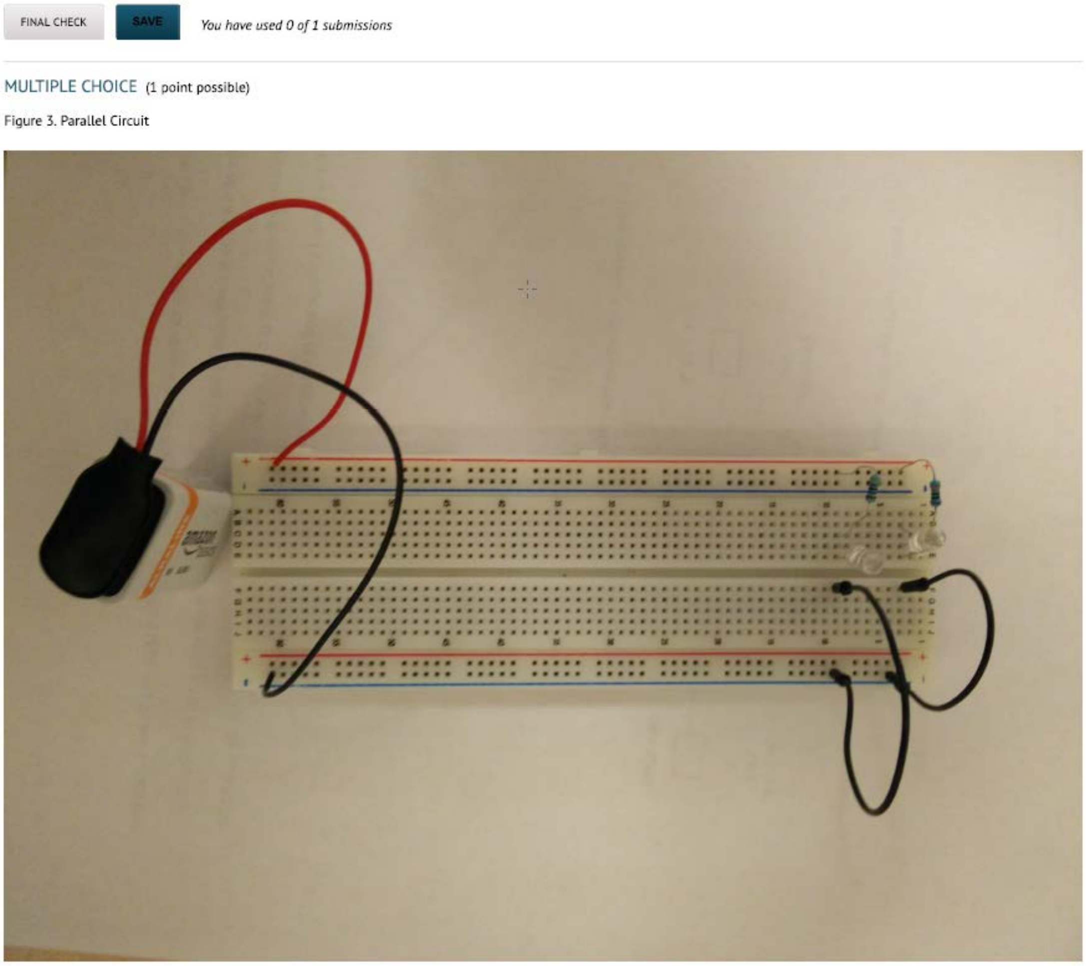
_____ is the difference in the electrical charge between two points; _____ is opposition to flow due to friction; _____is the movement of electrons in an electrical circuit.

○ **Voltage; current; resistance**

○ **Voltage; resistance; current**

○ **Current; resistance; voltage**

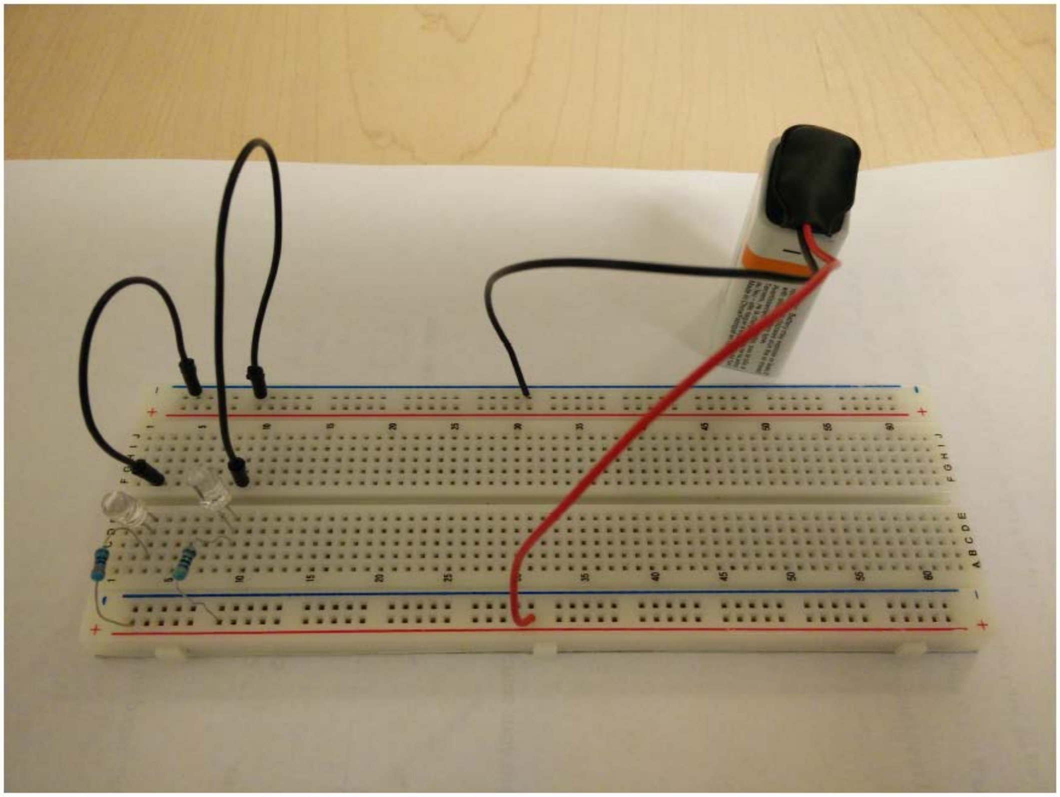
○ **Resistance; voltage; current**



You have used 0 of 1 submissions

MULTIPLE CHOICE (1 point possible)

Figure 3. Parallel Circuit



Using the two pictures above, identify the issues with how the circuit was constructed.

○ **The battery terminals are connected incorrectly and the resistance values are too high/low**

○ **The LED leads are in the same row and the wiring does not close the circuit**

○ **The resistance values are too low/high and the LED leads are in the same row**

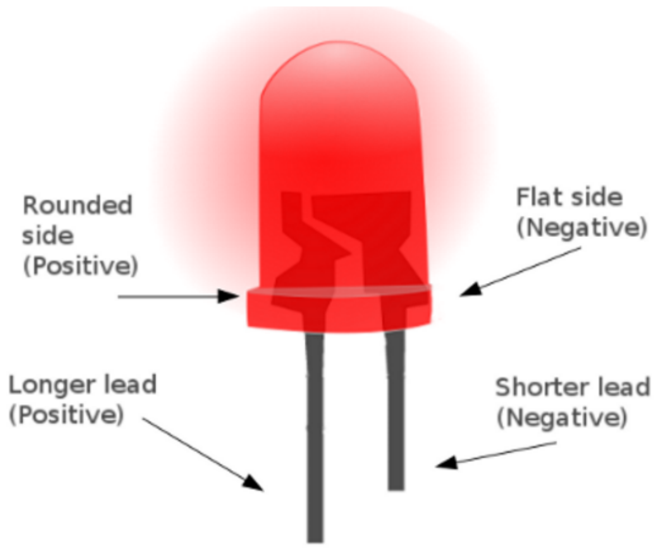
○ **The wiring does not close the circuit and the battery terminals are connected incorrectly**

Appendix K

Transition notes for participants in the 2D and 3D simulations

When constructing circuits on a physical breadboard here are a few things to consider:

- Components are smaller and may be more challenging to manipulate in the physical environment
- The appropriate resistor must be selected using the resistance band chart (as opposed to typing in the value)
- The breadboard may be oriented differently
- The positive lead of the LED (represented by the crooked lead in the simulation) is longer than the negative lead (*see the figure below*)



- If the circuit is not functioning, it may be the result of blown LEDs, dead battery, or components not inserted correctly

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