Paper ID #16534

Understanding Learner's Mental Models of a Task as Shaped by the Physical Fidelity of a Learning Environment

Ms. Myrtede Christie Alfred, Clemson University

Myrtede C. Alfred is a PhD student in the Department of Industrial Engineering at the Clemson University. She received her M.S in Industrial Engineering from Clemson University in 2013 and a BBA in Human Resources Management from Florida International University in 2009. She is graduate teaching assistant in the Department of Industrial Engineering. She is also a Southern Regional Education Board Fellow and Clemson University Diversity Fellow. Her research focuses on the use of virtual reality in facilitating learning in online environments.

Morris Branchell Lee III

Dr. David M. Neyens, Clemson University

David M. Neyens, PhD MPH, is an assistant professor of industrial engineering at Clemson University. He received his PhD in industrial engineering from the University of Iowa in 2010 and a MPH from the University of Iowa in 2008.

Dr. Anand K. Gramopadhye, Clemson University

Dr. Anand K. Gramopadhye's research focuses on solving human-machine systems design problems and modeling human performance in technologically complex systems such as health care, aviation and manufacturing. He has more than 200 publications in these areas, and his research has been funded by NIH, NASA, NSF, FAA, DOE, and private companies. Currently, he and his students at the Advanced Technology Systems Laboratory are pursuing cutting-edge research on the role of visualization and virtual reality in aviation maintenance, hybrid inspection and job-aiding, technology to support STEM education and, more practically, to address information technology and process design issues related to delivering quality health care. As the Department Chair, he has been involved in the initiation of programmatic initiatives that have resulted in significant growth in the Industrial Engineering Program, situating it in the forefront both nationally and internationally. These include the Online Master of Engineering in Industrial Engineering Program, the Endowed Chairs Program in Industrial Engineering, Human Factors and Ergonomics Institute and the Clemson Institute for Supply Chain and Optimization and the Center for Excellence in Quality. For his success, he has been recognized by the NAE through the Frontiers in Engineering Program, and he has received the College's Collaboration Award and the McQueen Quattlebaum Award, which recognizes faculty for their outstanding research. In addition, Dr. Gramopadhye serves as Editor-in-Chief of the International Journal of Industrial Ergonomics and on the editorial board for several other journals.

Understanding learner's mental models of a task as shaped by the physical fidelity of a learning environment

Abstract

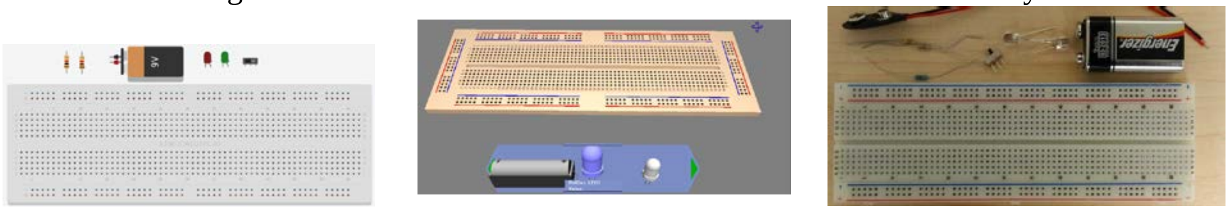
The purpose of this research is to identify how different levels of physical fidelity – a 2D simulation, a 3D virtual environment and a physical environment- impacted the proficiency of participants who learned to construct a circuit on a breadboard. In an initial study, the researchers identified differences in proficiency, defined by circuit construction time, diagram accuracy, and correct circuit construction among participants in the three conditions. The results of this initial study, while providing valuable data about the outcomes achieved by the participants, offered little insight into the processes or mechanisms through which the physical fidelity impacted the results. In this follow-up study, the researchers sought to understand why students demonstrated significant differences in proficiency between conditions and whether these differences were related to the physical fidelity of learning environment. Semi-structured interviews were conducted to understand the experience of participants in the different learning environments. A purposeful sample of 20 participants was recruited for the study. Analysis involved coding the transcribed interviews, developing dimensions and properties for these codes and then generating themes related to the effects of the physical fidelity of the learning environment. The study identified differences in the level of support and procedural differences in the circuit construction process in the 2D and 3D environments that contributed to deviations in performance. Additionally, the study found differences in the affect of the students learning in the computer environments that impacted performance. The findings of this study provide valuable insights about how the physical fidelity impacted participant's performance. These results can be used to better design and integrate computer mediated environments in technical education.

Introduction

When evaluating disparities in the performance of individuals using various types of technology, research studies have typically attributed statistically significant differences in performance to the technology.[1, 2] However, these differences in performance may stem directly from the technology, the human computer interaction, or from characteristics of the individuals using the technology. Very few of these studies have sought to understand how the differences in technology contributed to deviations in performance. The purpose of this study is to use qualitative methods to further understand how the learning environment impacts the performance of individuals on an electric circuit construction task.

In a previous study, Alfred, Neyens, and Gramopadhye sought to evaluate how an individual's performance on a task (i.e., constructing a circuit on a breadboard), varied depending on the physical fidelity of the learning environment.[3] Specifically the study investigated learning to construct electrical circuits using a 2D breadboard simulation, a 3D breadboard, and a physical breadboard (figure 1). The participants included 48 undergraduate and graduate students from a large public university in the southeastern US. These participants were randomly assigned to one of three levels of fidelity where they learned to construct a circuit on a breadboard. Statistical analysis of participants' pre-test scores found that participants in each condition were comparable in terms of prior circuit knowledge.

Figure 1. Breadboard used in three conditions for the initial study



A. Screen shot of the Arduino 2D Breadboard (123d.circuits.io)

B. Screen shot of the NI Multisim 3D Breadboard

C. 800 Point Solderless Breadboard

The results from this study found that the physical fidelity of the learning environment was a significant predictor of self-efficacy, circuit construction, and construction time.[3] While this study provided good data about the influence of physical fidelity on learning outcomes, it did not provide insights about why learners in the physical condition had higher self-efficacy, lower construction times and a higher likelihood of correctly completing the construction task than participants in the other two conditions.

The theory of identical elements suggests that the more similar the learning environment is to the transfer environment, the higher the transfer.[4] This theory provides justification for the superior performance of participants who learned to construct the circuit in the physical environment. While some differences were expected, the differences were very large, particularly with respect to the construction time. On average, participants in the physical condition constructed the circuit in half the amount of time required for participants in the other two conditions. [3] Additionally, this theory does not explain differences in self-efficacy among participants in the three conditions.

In this follow-up study, the researchers sought to understand why students demonstrated significant differences in proficiency between conditions and whether these differences were related to the physical fidelity of the learning environment.

Methods

The study was approved by the Institutional Review Board of [University named omitted for review] (IRB # 2015-001). The study used a purposeful sample of 20 participants who had participated in the original study. The participants were chosen in a way to ensure that the study included participants who are:

- Representative of those in each experimental condition (i.e., physical, 2D simulation and 3D)
- 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 1. Participants

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

Study Procedures

Once participants signed the consent form they were given a short briefing that explained the purpose of the study. They were then informed about the structure of the study and were provided with an opportunity to ask questions. After the briefing, a semi-structured interview was conducted with each of the participants to learn about 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 of the study. 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.[5] After several interviews the researcher revisited the notes from the individual interviews and then compared the notes to identify trends.[6] This process was repeated with every four set 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, feeling, and preconceptions about the phenomena being studied.

After all of the 20 interviews were completed, the researcher defined an initial set of concepts using the memos from the interviews as well as the transcriptions. Thoughts, quotes and paraphrased excerpts from the different interviews were grouped based on similarity using a process comparable to an affinity diagram. These groups of concepts were then used to define categories. Categories represent higher level abstract concepts that are similar in nature and can be contrasted by their properties. [5]

The categories generated from the previous process were used to code the transcriptions using Dedoose, a qualitative and mixed methods research software. Sentence fragments, sentences, and whole sections of interview data were coded based on the main idea being conveyed by the participant. The 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 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 categories as well as their properties.

Analysis

The initial concepts were derived from both participant quotes and the researcher's memos. The researchers focused on key aspects of the interviews, the memos taken after each interview, and the trends identified from revisiting these memos. Below is an example of a direct quote from a participant discussing his affect after he successfully constructed 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 help 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 together 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 2.

Table 2. High level categories generated from concepts extracted 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

The 20 interviews were then coded separately by two members of the research team using Dedoose. Once all of the interviews were coded, the properties and dimensions of the categories were defined. Properties describe the general characteristics of a category and dimensions describe the location of the property along a range or continuum. [5] For two of the 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. [7] Emotional state was evaluated in terms of valence – negative to positive – and arousal – low to high.[8] The researchers defined the properties and dimensions for the remaining seven categories as shown in Table 3.

Table 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
Emotional state	• 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

The research team then began searching for trends among the categories and properties within those categories 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, varied highly among participants but appeared unrelated to the physical fidelity. Participants described prior courses and informal setting 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. Participants discussed their relationship with the researcher, general interests in research, “research karma,” as well as the financial incentives for participating. For self-descriptions participants tended to relate their major, their learning preference and/or their personality to their performance. Some also used these descriptions to explain their preference for one learning environment (such as the physical) over the other (such at the 2D or 3D environments).

The categories that were most affected by physical fidelity were the described characteristics of the learning environment, attributions, affect, strategies and tactics. The former three categories also had 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 which help explain how the physical fidelity of the learning environments impacted performance. These themes are level of support, physical transition, and emotional transition.

Theme 1: Level of support

Participants in the computer environments, and specifically the 3D environment, often referred to higher levels of support in these environments compared the physical environment.

Participants who practiced in the 3D condition spoke of specific attributes of the 3D environment 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 noted this as:

> “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 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 computer environment concerned the level of feedback. Participants in both the computer 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 your 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 maybe 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 to during the construction process on the physical breadboard. This theme also included the participant’s assessment 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 computer environments 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. Several even mentioned trying to recreate the circuit directly from memory.

In terms of the step by step process that participants 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 in participants in the 2D condition concerned visualization and mental rehearsal. Participants in the 2D simulation described trying to mentally construct the circuit in the condition in which they learned 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 attributions than participants in the computer environments and also made more positive attributions. They spoke about the recency of practice and the helpfulness of the videos. When discussing some of the reasons for their struggles, participants in the computer 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 computer 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 computer environments to the physical environment was the orientation of the breadboard and the components. Below two participants noted 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 computer environments to the physical environment described a wide range of emotions related to the transition. Some participants spoke of a downward shift of confidence that resulted from performing without obstacles in the computer 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 greater satisfaction for those participants 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."

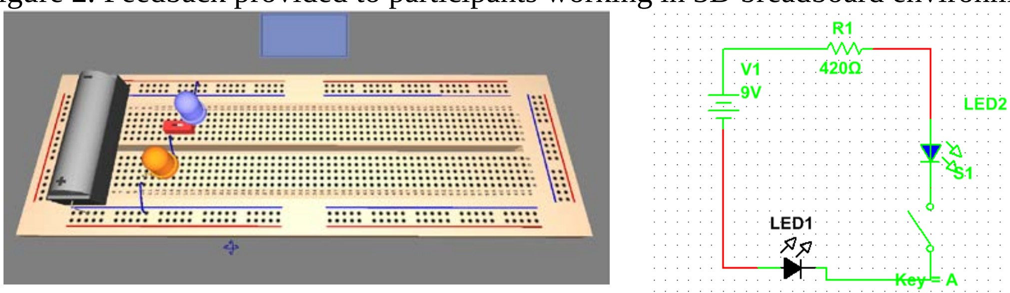
> "Uh, the other thing I said was that when you go, when you do it physically, like the stakes feel a lot high, the emotional stakes felt a lot higher like you were more like down when something didn't work and you were more like excited when it did work and part of that might have been the fact that 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 maybe 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

The three themes that emerged from the analysis were level of support, physical transition and emotional transition. The level of support focused on attributes of the computer environments, 2D and 3D, that helped participants successfully complete the practice activities. These characteristics included positive feedback, zooming capabilities, alternate viewpoints and simpler manipulation of components. The attribute of the learning environment described as having influenced performance the most was feedback. In the virtual environment, participants could switch views between the circuit diagram and the breadboard to ensure that they were constructing the circuit correctly. The diagram would show green lines for correct connections and red lines for the incorrect connections (figure 2). This feedback provided by the computer environments appears to have both beneficial and detrimental effects. Participants found it really helpful to have feedback during the practice session, particularly in the virtual environment. It provided them with visual information concerning where an error was 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 the dual affect of feedback specificity, which describes the amount of information provided to learners in feedback messages. [9] Previous studies suggests that high feedback specificity is beneficial for immediate performance but reduce learning opportunities needed for independent performance. [8]

Figure 2. Feedback provided to participants working in 3D breadboard environment



A.
Breadboard view

B.
Diagram view

The theme of physical transition focused on the approach participants used to during the construction process on the physical breadboard and the effectiveness of this approach. The approach participants used can be described on a scale ranging from methodical to trial and error. Most participants used an approach that fell somewhere in the middle but participants in the computer environment appeared more comfortable using a trial and error approach. One possible explanation for this involves the adaptations required for the participants who transitioned from the computer environments. Unlike the participants in the physical condition who did not have to adapt their performance, participants in the computer environments were forced to deal with differences in the construction procedures, such as reading the resistor versus typing in the resistance value, which made it difficult to follow the exact steps they did in the simulation. As a result, it was necessary for them to perform some trial and error in 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. This additional step in the construction process appeared to be a mechanism participants' in this condition used to recall the procedures they learned. In both statements the participants describe using 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."

When it came to manipulating components, participants spoke of some difficulty working with the small physical components. However, the orientation of the breadboard appeared to be particularly problematic. The orientation of the breadboard in the 2D simulation was horizontal and could not be changed. The default orientation of the breadboard in the 3D environment was horizontal but it could be changed. For physical construction, the breadboard was arranged vertically but participants could, and several did, change the orientation. For participants who did not immediately change the orientation of the breadboard, this potentially represented an unnecessary increase in cognitive load. [10] 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."[11]

Another theme that emerged related to the emotion state of participants in the 2D simulation. The emotional transition theme describes the affect of participants when they transitioned from the computer environment to the physical environment. Participants described two predominant emotion states related to the transition; decrease in confidence and heightened emotional divergence. Participants who performed successfully in the computers environments during practice and then struggled in the physical condition described experiencing a "downward slope" of confidence. The drop in confidence for the participants was not simply the result of encountering these obstacles but feeling ill-prepared and being unable to overcome these obstacles. Prior research has suggested that information processing capabilities are reduced when dealing with negative emotions. [12] Previous research in training has also found that learners who completed an instructional program without obstacles struggle when faced with obstacles in the performance environment. [12] 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. [9] Participants in the 2D simulation also described a heightened emotional divergence when they transitioned from the computer environment to the physical breadboard. They described becoming more frustrated when they could not get the circuit to work in the physical condition and they described increased "pressure." They also described more 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 is summed up but 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 computer environments. Another explanation deals with the task itself. Constructing a circuit on a breadboard is hands-on task. Having to do this "hands-on" task in a computer environment potentially detracted from both emotional engagement in the environment and well as the participants' perceptions of their ability to complete the task. This was evident in the previous study as participants in the computer conditions had statistically significantly lower self-efficacy than participants in the physical environment. [3]

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 and this potentially affected the interview data. A representative sample of 20 participants were interviewed, however, it may have been beneficial to conduct more interviews. The last limitation is that the interviews were conducted by 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 will need to reduce the level of support provided to participants. For example, the 3D breadboard software can progressively decrease the feedback provided to learners so that they have the help they need early in practice but are not hindered as they prepare for the transition. Both the 2D simulation and the 3D breadboard software can also facilitate the transition by requiring similar procedures to what is necessary in the physical environment. For example, allowing participants to choose the correct resistor by reading a resistance sheet is a more difficult task then allowing them to type in the resistance value. Additionally, the computer environments can make the participants aware of differences they may encounter when they transition. Transitions from these environments can be made smoother if participants are aware of issues present in the physical environment – blown LEDs, dead batteries, burnt connections on the breadboard – that do not occur in the computer environments. If participants are knowledgeable of these potential issues they can better troubleshoot issues with their construction.

There are some differences that will still 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. This simply does not translate from the computer environment. The other physical difference concerned 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. [3]

The other difference between the 2D and 3D environment and the physical environment concerned the participants' affect while working in those environments. Participants described feeling “intimidated,” “more pressure,” and having “higher stakes,” when transitioning from the computer environments to the physical environment. While the 2D and 3D cannot necessarily change these emotions, they can help build learners’ confidence and self-efficacy by providing them with knowledge needed for both constructing a circuit in that particular 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 – ease of use, multiple views, zooming capabilities, positive feedback – can offer a superior learning experience for students while also supporting high transfer.

Future Research

One of the most unanticipated finding from the analysis concerned the emotional transition participants faced when moving from the simulations and virtual environments to the real-world environment. Future work should examine the affect of students learning a skill in a computer environment and how their emotions evolve as they attempt to transfer skills learned in computer environments to real world applications. Future research should also examine whether the findings from this study are consistent across different tasks and different 2D and 3D implementations.

Acknowledgements

This work was supported by the National Science Foundation under Grant No. DUE-1104181. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This work was also supported by through a Clemson University Diversity Fellowship, the Bowen Graduate Fellowship and the Southern Regional Education Board Fellowship for the first author. The authors would like to thank the Ergonomics and Applied Statistics Laboratory at Clemson University for their reviews of this manuscript. The authors also extend a special thanks to Dr. Robin Phelps for her guidance on the analysis.

References

1. Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., ... & LeMaster, R. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. Physical Review Special Topics-Physics Education Research, 1(1), 010103.
2. Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). Computers & Education, 56(3), 769-780.
3. Alfred, Neyens & Gramopadhye. 2016.The Impact of Physical Fidelity on Skill Acquisition and Application. To be submitted to Computers & Education.
4. Goldstein, I. L., & Ford, J. K. (2002). Training in organizations: Needs assessment, development, and evaluation Wadsworth. Belmont, CA.
5. Strauss, A. L., & Corbin, J. M. (1990). Basics of qualitative research (Vol. 15). Newbury Park, CA: Sage.
6. Rubin, H. J., & Rubin, I. S. (1995). The art of hearing data. Thousand Oaks.
7. Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. Contemporary educational psychology, 25(1), 54-67.
8. Kensinger, E. A. (2004). Remembering emotional experiences: The contribution of valence and arousal. Reviews in the Neurosciences, 15(4), 241-252.
9. Goodman, J. S., & Wood, R. E. (2004). Feedback specificity, learning opportunities, and learning. Journal of Applied Psychology, 89(5), 809..

10. Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. Educational psychologist, 38(1), 1-4.
11. Regian, J. W., Shebilske, W. L., & Monk, J. M. (1992). Virtual Reality: An Instructional Medium for Visual-Spatial Tasks. Journal of Communication, 42(4), 136-149
12. Heimbeck, D., Frese, M., Sonnentag, S., & Keith, N. (2003). Integrating errors into the training process: The function of error management instructions and the role of goal orientation. Personnel Psychology, 56(2), 333-361.