Proceedings of the ASME 2021
International Design Engineering Technical Conference & Computers and Information in Engineering Conference
IDETC/CIE 2021
August 17-21, 2021, Virtual Conference

DETC2021- 71667

ANALYSIS OF THE KNOWLEDGE GAIN AND COGNITIVE LOAD EXPERIENCED DUE TO THE COMPUTER-AIDED INSTRUCTION OF ADDITIVE MANUFACTURING PROCESSES

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ABSTRACT

Although there is a substantial growth in the Additive Manufacturing (AM) market commensurate with the demand for products produced by AM methods, there is a shortage of skilled designers in the workforce that can apply AM effectively to meet this demand. This is due to the innate complications with cost and infrastructure for high-barrier-to-entry AM processes such as powder bed fusion when attempting to educate designers about these processes through in-person learning. To meet the demands for a skilled AM workforce while also accounting for the limited access to the range of AM processes, it is important to explore other mediums of AM education such as computer-aided instruction (CAI) which can increase access to hands-on learning experiences. Therefore, the purpose of this paper is to analyze the use of CAI in AM process education and focus on its effects on knowledge gain and cognitive load. Our findings show that when designers are educated about material extrusion and powder bed fusion through CAI, the knowledge gain for powder bed fusion is significantly different than knowledge gain for material extrusion, with no significant difference in cognitive load between these two AM processes. These findings imply that there is potential in virtual mediums to improve a designer's process-centric knowledge for the full range of AM processes including those that are usually inaccessible. We take these findings to begin developing recommendations and guidelines for the use of virtual mediums in AM education and future research that investigates implications for virtual AM education.

Keywords: Additive Manufacturing, Education, Cognitive Load, Computer-Aided Instruction, Material Extrusion, Powder Bed Fusion.

1. INTRODUCTION AND MOTIVATION

Additive manufacturing (AM) enables the design and rapid manufacturing of complex and optimized products by leveraging capabilities in geometrical, hierarchical, functional, and material complexity. There is therefore a high demand for the use of AM in product development as observed from the global AM and materials market which is projected to reach USD 70.92 million by 2026 [1]. There is considerable ongoing growth and development in processes, materials, and design for AM (DfAM) heuristics to support this demand for AM in the market. However, there is a deficit of designers and engineers in the workforce skilled in AM [2] who can apply the technology to a multitude of product design opportunities [3] and meet the high demand. Consensus on how to better prepare the AM workforce indicates a growing requirement for design and process-centric education that covers all AM processes [4]. As a result, there is significant work that aims to meet the requirement for adequate design-centric education [5–9]. Certain attempts to address the deficiency in design-centric skill even provide supportive tools for DfAM [5,6]. Other work includes educating designers through frameworks designed for particular systems or processes and although some of this work attempts to provide process-independent DfAM education [7], there is an observable process-dependent nature of many DfAM rules, guidelines, and frameworks [8,9]. This suggests that adequate process-centric education for the full range of AM processes can support the growth of DfAM intuition to improve a designer's versatility with AM thereby filling the deficit of designers. However, limited access to the full range of AM processes inhibits designers from gaining the required AM process knowledge base to improve their versatility. This limited access is attributed to the observable barriers to entry faced by AM systems (e.g., cost, safety, required infrastructure) [10–12] when introduced within educational institutions and communities.

To satisfy the growing demand for a skilled AM workforce, there is a need to address this inaccessibility to AM processes to better help develop a designer's process-centric background in AM. Our research, therefore, aims to analyze instructional methods that may better expose designers to the range of available AM processes to improve their process-centric knowledge. In our analysis, we aim to understand the effects of the instructional method on the observed knowledge gain and cognitive load experienced by student designers when they learn about different AM processes. Gaining insight from these metrics can establish the ease (or difficulty) experienced by the designer while improving their knowledge base in AM.

There is an opportunity to utilize immersive and non-immersive virtual mediums, such as virtual reality (VR) and regular, screen-based computer-aided instruction (CAI), for AM education. Limited research, however, attempts to educate designers on processes like powder bed fusion that require higher-barrier-to-entry systems [13], and no published work highlights the differences in virtual learning between two or more different AM processes. Our research aims to address this gap in the literature and analyze and compare the use of virtual mediums of education as tools in process-centric learning for different AM processes. The research in this paper highlights the key preliminary learnings from an analysis of a non-immersive virtual medium (i.e., CAI) for two AM processes (i.e., material extrusion and powder bed fusion). Our findings highlight the effects on knowledge gain and cognitive load experienced by designers when using CAI for process-centric AM education of these two different AM processes. These findings imply that there is potential in using CAI for the instruction of AM processes that are not easily accessible, thereby providing a complete and thorough education in process-centric AM to designers in the high-demand AM workforce.

2. RELATED WORK

The goal in this research is to contribute to the improvement of process-centric AM understanding in designers. This is done by testing virtual mediums for the hands-on education of different AM processes. This section provides background on the current challenges with AM education, identifies gaps in current education practices, and overviews alternative uses of virtual mediums for education.

2.1 Current challenges with in-person process-centric AM education

Recently identified recommendations from an NSF workshop on AM [4] aim to set important goals in AM education that can adequately prepare students and designers for the AM workforce. The recommendations and goals include cultivating student and designer awareness in:

1. Both additive and traditional manufacturing processes to better highlight the applicability of AM in product realization,
2. The range of AM processes, and materials to provide design for AM insight,
3. Computational tools for design as well as frameworks for process selection, costing, and solution generation to enable design and manufacturing with AM.

Such goals strongly suggest the need for in-depth and hands-on design and process-centric AM education to improve design for AM intuition in designers. Universities are already establishing initiatives to design frameworks for AM education [14], dedicate hands-on laboratories and curriculums through graduate programs [15], and offer certificates [16] and minors [17] to support and improve students' understanding of the design and process-centric concepts in AM. Some texts [18–20] are also proving to be useful resources that provide an overview on AM topics and technologies. Although these instructional tools, resources, and laboratory environments enable fundamental AM education, it is still challenging to provide scalable hands-on and in-depth experiences [4] to better prepare designers.

Limited access to the full range of AM processes presents the primary challenge for designers when they attempt to gain the required AM expertise for product development. This limited access is due to the barriers to entry faced by AM systems (as dictated by cost, safety, or required infrastructure) when introduced within educational institutions and communities. While low-barrier-to-entry systems, such as those for material extrusion, are accessible to students in an engaging, safe, and cost-effective way, the larger and more complex systems, such as those for powder bed fusion, are too expensive [10] or dangerous to be in classroom environments without sufficient infrastructure in place [11,12]. For example, AM systems for powder bed fusion can contain hazardous sub-systems such as lasers, combustible powder, high temperatures, and pinch points, and hence require adequate safety measures in place before allowing user interaction. This can be challenging and costly to provide which may prevent institutions, companies, and communities from adopting in-person exposure to powder bed fusion systems in their AM education [11]. AM education for such systems and processes may instead be done in the traditional classroom environment or through independent agencies in an informal and unstructured manner [21]; however, there is limited accessibility to hands-on opportunities outside of the classroom and limited agreement on texts and pedagogies that meet the requirements set by the Accreditation Board for Engineering and Technology (ABET) [11]. The lack of an accessible, scalable, and thorough method of conducting process-centric AM education for the range of AM processes creates an imbalance in AM knowledge in students and designers. This imbalance in knowledge from current AM education is driven by the innate challenges of in-person education. There is therefore a need to explore the use of virtual hands-on mediums of education that expose designers to the diverse range of AM concepts engagingly and interactively.

2.2 Virtual instruction as an alternative in design, engineering, and manufacturing education

There is a need to provide accessible and in-depth education to the range of AM systems and their intrinsic DfAM principles. Due to the limitations of in-person instruction for more industrial AM systems, such as those for powder bed fusion, there is an opportunity to instead utilize immersive and non-immersive virtual mediums, such as virtual reality (VR) [22,23] and CAI, in AM education. Virtual mediums can provide hands-on learning experiences engagingly and interactively while avoiding some of the limitations of in-person learning. Literature even shows early promise in developing designer intuition in design and process-centric AM concepts [24–26] using virtual education. The goal in this research is to evaluate both immersive and non-immersive virtual mediums in process-centric AM education for different AM processes. This paper focuses on the effects of CAI on knowledge gain and cognitive load when designers learn about material extrusion and powder bed fusion.

There are several observable benefits to using CAI for education in science [27,28], engineering [29–31], and manufacturing [32–36] as an alternative to in-person learning. Non-immersive CAI experiences that contain pedagogical elements reduce the challenges with in-person learning [35], impart new knowledge onto the learner [37–39], and improve the quality of learning in collaborative problem-solving situations [39]. Pantelidis [40] also suggests that virtual and interactive environments used in engineering education promote motivation, more accurately illustrate some features or processes, and are more inclusive to the disabled. Additionally, CAI is known to improve psychomotor skills for operations in manufacturing applications [30] and improve entry-level engineering education in students [31] while showing no loss of educational effect [29] when compared to in-person education. The benefits of using CAI in engineering and manufacturing education indicate viability for CAI-driven AM education in preparing designers for the high-demand AM workforce. Past work by Tseng et al. [26] shows an emergence of virtual education for AM. Their work in computer-aided instruction of process-centric AM concepts not only suggests that there is no statistically significant difference in knowledge gain between those who learn through a CAI experience versus those who learn in-person but there is also a strong interest and preference toward learning through CAI [26]. This work shows that virtual mediums of education can offer effective alternatives to in-person AM education.

Just like the goal of this research, Tseng et al. [26] also analyzed knowledge gain in students when they were educated on process-centric AM concepts using a virtual medium of instruction. Ostrander et al. [25] also highlight the value in understanding the effects on knowledge gain through virtual education. However, both these works only focused on one AM process (i.e., material extrusion). There is an opportunity to expand on this work by exploring and comparing effects in learning when students are taught about different AM processes. Furthermore, there is an opportunity to understand the ease or difficulty experienced by designers during their learning experience as measured by the experienced cognitive load. No known research highlights the differences in learning and cognitive load when comparing the virtual education of two or more different AM processes. This research aims to address this gap in the literature and analyze and compare the use of CAI as a tool in process-centric learning for different AM processes. This paper highlights the key preliminary learnings from an analysis of a knowledge gain and cognitive load for two AM processes (material extrusion and powder bed fusion).

3. RESEARCH QUESTIONS

Based on this previous work, the goal of the current paper is to analyze the effects of computer-aided instruction of process-centric AM concepts on knowledge gain (as measured by the change in quiz score) and cognitive load (as measured by self-reported values). Specifically, we address the following research questions while comparing two AM processes: material extrusion and powder bed fusion.

RQ1. How do the functional differences between material extrusion and powder-bed fusion affect knowledge gain when learning about these AM processes?

We hypothesize that knowledge gain between the two processes will differ due to inadequate education being provided for the powder bed fusion AM process. We believe that this inadequacy is attributed to the inaccessibility to powder bed fusion systems for hands-on learning experiences.

RQ2. How do the functional differences between material extrusion and powder-bed fusion affect cognitive load when learning about these AM processes?

We hypothesize that the cognitive load experienced between the two AM processes will differ because the tasks, parts, and required motor skills needed to interact with the machines for the AM processes may be perceived to be of different complexity.

4. METHODOLOGY

4.1 Overview of the experimental procedure

Designers were introduced to virtual environments where they could interact with an AM system while being verbally instructed on different process-centric concepts for the AM process. The goal for the designed environments was to reflect the fidelity of in-person learning environments. However, doing so can require extensive computational resources; therefore, the designs needed to be optimized for fidelity and web performance (i.e., reduced lag during the experiences and higher frame rates in performance). So before evaluating knowledge gain and cognitive load, our preliminary testing identified several shortcomings of web performance in CAI. The methodology during preliminary testing, therefore, involved evaluating two parent studies of varying web performance, under which there were experimental conditions for each of the two AM processes. The two parent studies differed as follows:

S1. This pilot study was conducted using the basic versions of the web-based experiences to set up the actual study.

S2. This study was conducted using refined versions with improved web performance and was used to collect data for analysis of knowledge gain and cognitive load.

The primary difference between the two studies was therefore only technical improvements in web performance. A total of 54 students participated across the two studies. Table 1 shows the distribution of participants across the four conditions.

TABLE 1: Distribution of participants across each study and across each process condition.

Study	Process	Number of Participants
S1	Material Extrusion	2
	Powder Bed Fusion	19
S2	Material Extrusion	26
	Powder Bed Fusion	8

The participants for this research were recruited were from an introductory engineering design course from an R1 university.

Participants volunteered either individually or in groups. Groups were assigned the same process condition while individual volunteers were assigned to a process condition randomly. For all the conditions, participants completed the steps highlighted in Figure 1 during their participation.

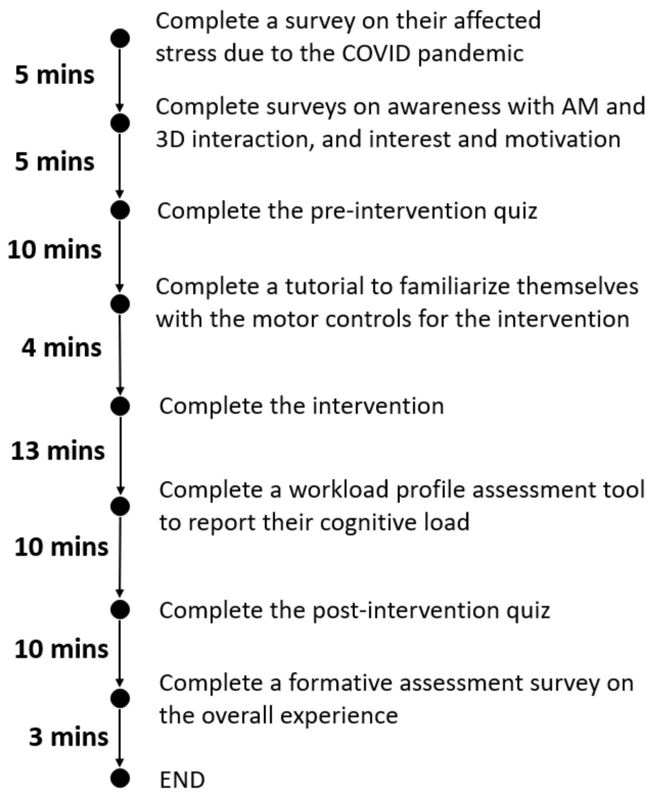


Figure 1: Illustrating the procedure participants completed for all the conditions. The total allotted time was 60 minutes.

While a maximum of 60 minutes was allotted to participants, only the 17 minutes constituting the tutorial and the intervention were fixed. For the other steps, participants were given the freedom to complete the steps at their own pace. This means that participants could complete the study before the end of the allotted time but were not allowed to proceed after the time limit. On average, however, participants spent 40 minutes for the study in either condition, therefore no participant was excluded from the data set due to exceeding the study's time limit.

Participants were first asked to complete a survey assessing the impact of the COVID pandemic on them and how much it affected their stress within the previous week. The listed sources of stress relevant to the COVID pandemic were:

- Changes in routine (CIR)
- Fear of getting sick (FGS)
- Fear of friends and family getting sick (FFS)
- Doing well in school or at work (DWS)
- Using the technology needed for classes or work (UTC)
- Access to a reliable internet connection (ARI)
- Access to a place to do work (APW)
- Juggling with other responsibilities besides work (JUG)
- Managing the overall situational changes due to the pandemic (OVR)

This data helped to understand the participant's condition before the intervention and helped strengthen the analysis on cognitive load by indicating the presence of underlying trends due to the COVID pandemic in their reported scores. Participants then provided information on their prior exposure to AM and highlighted their awareness, length, and sources of exposure in AM concepts [41]. They also at this time indicated their interest and motivation levels for participating in the study [41].

Participants then completed the pre-quiz intervention which assessed their knowledge of process-centric AM concepts [42]. This data helped set an initial comparison point for knowledge gain [25]. The questions in the quiz were formulated using the same terminology as used verbally in the intervention to ensure there was little confusion in comprehension. They were also drafted to test participants' grasping of fundamental knowledge of AM process concepts derived from the Williams et al. [43] functional decomposition framework as highlighted in Section 4.2. All the questions were objective, single-answer, or multiple-answer type questions to ensure simplicity in calculating the quiz-scores and knowledge gain through the change in quiz scores. Every question offered an "I don't know" option to encourage honest responses and minimize the probability that students would accidentally pick the correct answer thereby providing misleading data. The scoring for each question was valued at 1 point in total with partial credit offered for the multiple-answer questions that still amounted to a maximum of 1 point. No negative scoring was done. All incorrect options were awarded 0 points.

Participants next completed a timed tutorial session (4 minutes) where they were given instructions for the keyboard and mouse controls and given time to practice with these. During the tutorial, participants were instructed on how to use the motor controls available to them to interact with, and navigate through, their computer environment. They were asked to perform practice tasks to reinforce their learning. The goal for the tutorial was to equalize any variation in skill participants had with prior CAI experiences similar to this research. After going through the brief tutorial, participants completed the timed intervention (13 minutes) in which they were exposed to the different process-centric concepts for their assigned AM process (see Section 4.2).

Upon completing the intervention, participants reported their cognitive load to share their perceived difficulty of their experiences. To capture the difficulty the participants perceived the different experiences to be, participants were asked to complete the Workload Profile Assessment (WPA) developed by Tsang and Velazquez [44] to measure cognitive load. This tool was selected due to the validity evidence in support of its use and because of its non-intrusive nature when compared to other multidimensional subjective workload assessment instruments [45]. Additionally, Rubio, et al. [45] found that the Workload Profile Assessment was the most sensitive when compared to the Subjective Workload Assessment Technique and the NASA Task Load Index. Participants provided scores for each of the eight dimensions of the workload profile assessment after completing the intervention. They provided a number between 0 and 10 to represent their cognitive load for each workload profile dimension. Due to the short length of the intervention, the cognitive load values were collected for the experience as a whole and not for each task that was completed. Analysis was done on these values as a grouped dependent variable. To ensure that the participants provide the most accurate measurements they can, each participant was provided with both a textual and pre-recorded audio description for each workload profile dimension. Participants were required to listen to the full audio description before proceeding, therefore this ensured that all participants received the same quality and quantity of information for their assessment. In addition, participants were given an example of how cognitive resources for each dimension might be applied to a relatable task to better evaluate their cognitive load.

Participants then completed the post-quiz, which assessed their change in knowledge as impacted by the intervention. Paired with the data from the pre-quiz, this data was used to measure knowledge gain as measured by the difference in quiz scores [25]. Using the functional classification framework [43] ensured that the pre-and post-quizzes asked identical questions related to the same concepts to provide an on-par comparison in knowledge gain between the two processes; however, certain concepts required adding additional questions to the quiz to ensure that all the relevant elements in the concepts were tested. Therefore, the number of questions differed between the two conditions (i.e., ME had 10 and PBF had 9). To account for the difference in number of questions, the difference in scores for each participant between the pre-and post-quizzes was calculated after tallying and normalizing the quiz scores. Normalization means that the entire set of scores was rescaled between 0 and 1 for both the quizzes using the min-max feature scaling approach. Statistical analysis for knowledge gain was performed on the normalized change. The difference score was regressed on the AM process conditions to analyze for statistically significant differences in knowledge gain between the two conditions.

Finally, participants filled out a formative assessment of their experience where they offered objective and subjective feedback for their experience. The subjective feedback from the comments was categorized into a "type of comment" and was quantified accordingly. The difference in frequency for the types of comments was used to assess the qualities of the web-based CAI experiences between S1 and S2.

4.2 Design of the intervention

Although there are several frameworks for process-centric education [46], we chose the work by Williams et al. [43] for this study because it has been successfully used to design pedagogies for higher-level education of AM design and process-centric concepts [6,14,47–49] in an academic learning environment. Using the framework by Williams et al. [43] also offered a structured foundation to design educational experiences for both material extrusion and powder bed fusion. This framework offered a functional classification of different AM processes that allowed us to extract key functional elements to design our process-centric education for both material extrusion and powder bed fusion. The functional classification of AM processes from this work was used to design a functional decomposition framework (see Figure 2) that allowed for a comparison between the two process conditions and provided comparable results in knowledge gain and cognitive load.

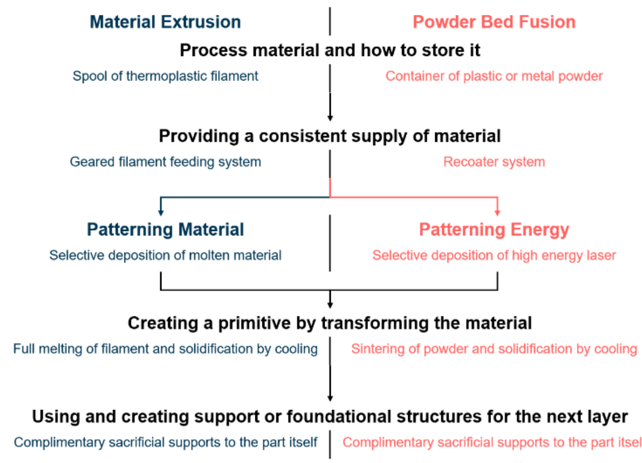


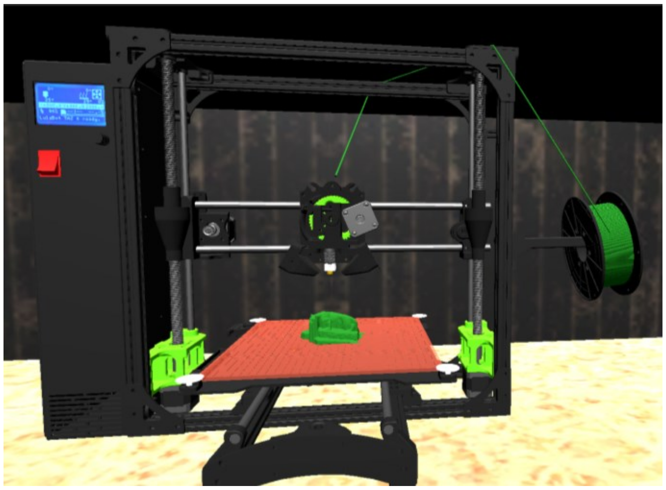
Figure 2: Highlighting the concepts derived from the Williams et al. [43] functional classification framework that are used to design the educational experiences and define the relevant tasks.

The simulated environments for the tutorials and interventions were designed as web applications using Unity, a cross-platform game engine popularly used to design virtual experiences. For the tutorials, the virtual space consisted of two arbitrary objects (a Nittany lion, and a Rubik's cube) on a desk that participants used to practice their motor skills. For the interventions, the virtual space consisted of two additively manufactured parts (one with support material intact, one without) on a desk, the source of raw material for the AM process, and the machine for the AM process. The Lulzbot Taz 6 was the system simulated for the material extrusion condition with a spool of filament next to it on a desk, while the Xact Metal XM200C, a laser-based system that fuses powder to make parts, was simulated for the powder bed fusion condition with a container of powder next to it on a desk

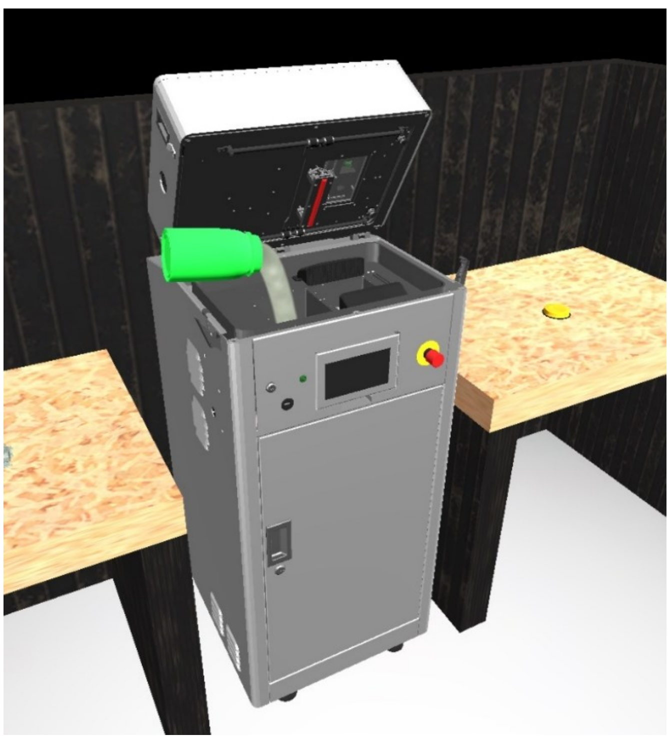
The typical steps participants would undergo in this virtual space during the instructional intervention involved first being introduced to a brief explanation for a particular AM concept, followed by a timed pause for them to execute any necessary motor operations to complete the task associated with the concept. The timed pause would range between 15-60 seconds depending on the perceived complexity of the task. Figure 3 illustrates a 60-second-long sample task performed during the intervention for both conditions. The goal for this sample task was to educate participants about the raw material used for the AM process and how and where it is stored in the system.

Participants were verbally educated on the raw material for the system and were then encouraged to load the material into the system. This design approach encouraged participants to actively engage with the virtual systems and their surroundings as they would have with the real systems in an in-person environment.

The design of the intervention was done to reflect the fidelity of in-person and hands-on learning experiences.



a) Loading filament into the extruder head



b) Adding powder into the powder bin

Figure 3: Illustrating the task associated with providing or supplying new material into the machine for the two different AM processes.

By facilitating an identical learning environment, this research hoped to analyze the effects of virtual learning while minimizing or enabling the advantages and disadvantages offered by virtual learning. Specifically, the goal was to minimize the effects of visual user interface features such as subtitle text, play, pause, or repeat buttons, highlights or guiding animations, and pop-ups or tooltips. This design approach played a significant role in how information was conveyed to the participants and how the tasks to be performed during the intervention were designed. As a result, participants were only provided with verbal instructions. These instructions included educational information on process-centric AM concepts and guidance to perform certain tasks to help reinforce the concepts conveyed.

Tasks were constrained to those that would be possible and permitted in a typical in-person learning environment with the real systems. This means that while participants were educated on the equivalent concepts in both conditions, participants were not instructed to perform some types of tasks. For example, tasks that were deemed dangerous (such as moving or interacting with a laser) or were simply restricted by the physical systems, were not part of the instruction. Since the organization of the tasks and the tasks themselves were specialized for the condition itself, there could not be any observable confounding interactions between the effective completion of the tasks. All tasks were therefore designed to be independent of each other; i.e., whether the participants succeeded or failed in completing the task did not affect the next task or concept conveyed in the intervention. Therefore, this work did not determine a task to be successful or failed and allowed participants to progress freely.

5. RESULTS

This paper uses linear model regression for all its statistical analyses with a sample size of 34 participants. The assumptions for using this approach were validated based on the work by Peña & Slate [50]. While validating the five assumptions for linear model regression, it was observed that the normality assumption for the analysis was not satisfied for some datasets. This section, therefore, highlights the findings from the data collected and its regression analysis results while relying on the robustness of linear model regression to non-normality [51,52].

TABLE 2: Highlighting the distribution of participant awareness in AM before the intervention.

Option	Count
I have never heard or learnt about additive manufacturing or 3D printing before this.	2
I have some informal knowledge/education about additive manufacturing (3D Printing).	13
I have received some formal knowledge/education on additive manufacturing (3D Printing).	18
I have received lots of formal knowledge/education on additive manufacturing (3D Printing).	1
I am an expert on additive manufacturing and can proficiently print parts.	0

The data collected from the surveys on AM awareness helped identify the diversity of experience in the dataset present prior to effects from the intervention. Table 2 shows the distribution of prior experience participants had with AM and suggests that many participants had some form of informal or formal experience with AM. This research also evaluated the interest and motivation of the participants in participating in the study. Results from the survey that collected information on participants' interest and motivation levels before their participation are shown in Figure 4. Most participants agreed that they were motivated and interested to use and learn about AM.

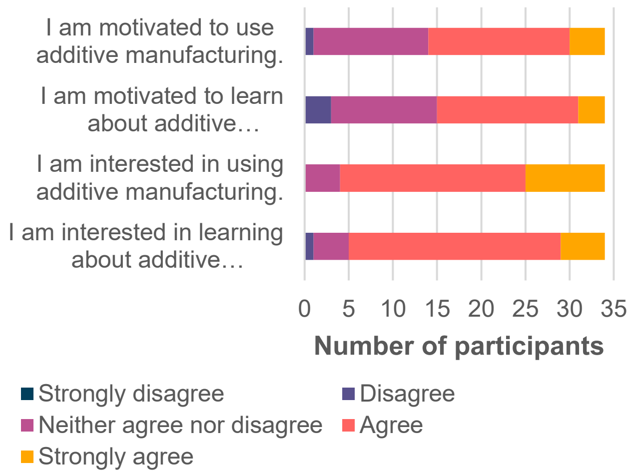


Figure 4: Illustrating the distribution of interest and motivation levels for each aspect of the participation.

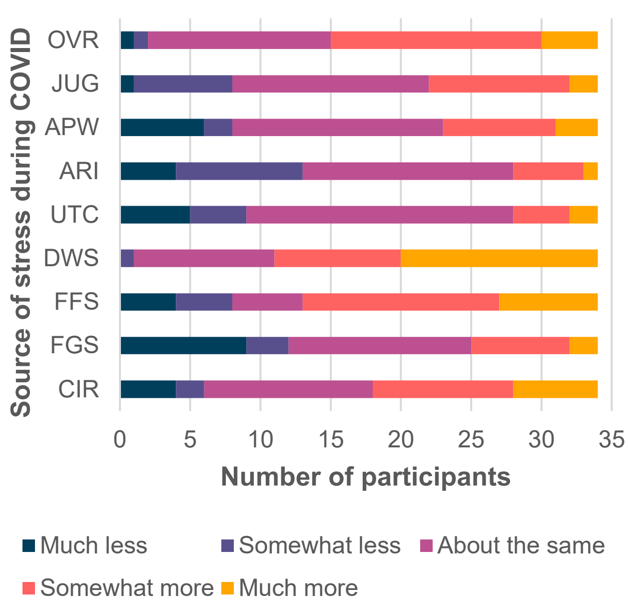


Figure 5: Highlighting the influence on the participants' stress levels by the COVID pandemic.

An additional assessment of participants' stress levels as influenced by the COVID pandemic (see Figure 5) identified if participants in either condition were under significantly different stress before participating. According to Figure 5, most participants felt that the listed sources of stress influenced them either about the same or more than they did within the last week.

We estimated a simple linear regression model in which we regressed participants' awareness of AM, interest and motivation levels, and COVID stress levels on the centered process condition (PBF= -0.5, ME= 0.5). We did not observe a significant difference in any of these dependent variables between the two conditions. These preliminary results indicate that participants in both the conditions were not significantly different in AM awareness, interest, and motivation to use and learn AM, or prior cognitive condition due to COVID-related stress. Therefore, effects observed in knowledge gain and cognitive load were attributed to the design of the intervention and effects of the medium only.

5.1 Knowledge gain as affected by the differences between the AM processes

The first research question in this study was developed to understand how the differences in AM processes affected knowledge gain as measured by the difference in quiz scores. Figure 6 highlights the distribution of the quiz scores for each condition. We hypothesized that the knowledge gain between the two processes (material extrusion and powder bed fusion) will differ due to the difference in accessibility to the AM process for the two processes. To study this, a linear regression model approach was applied to the data where the difference score was the only dependent variable, and the AM process was the only independent variable. The difference score was then regressed on the AM process for the analysis which identified significant differences in knowledge gain between the two conditions. No assumptions for parametric linear regression were violated.

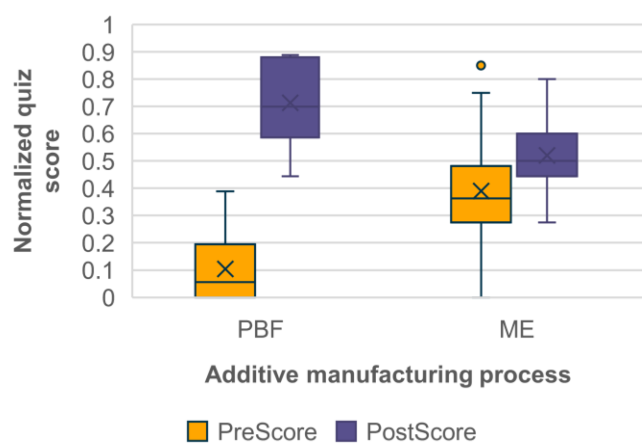


Figure 6: Illustrating the differences in knowledge gain between the two AM process conditions as shown by the pre- and post-quiz scores.

From the estimated simple linear regression model in which we regressed the difference score on the centered process condition (PBF= -0.5, ME= 0.5), we observed a statistically significant difference in knowledge gain between both AM process conditions, $F(1,32) = 37.87$ [$t(32) = -6.154$], $p = 6.96e\text{-}07$. The regression equation was: knowledge gain = 0.369-0.478*(Centered AM Process). The knowledge gain for the participants in the powder bed fusion process condition was therefore 47.8% higher than knowledge gain for the participants in the material extrusion condition.

5.2 Cognitive load as affected by the differences between the AM processes

The second research question in this study was developed to understand how the differences in AM processes affected the cognitive load experienced during learning as measured by the workload profile assessment tool. We hypothesized that the cognitive load between the two processes (material extrusion and powder bed fusion) will differ for the two processes due to the difference in perceived complexity of the tasks, parts, and required motor skills to interact with the AM process.

To study this, a linear regression model approach was applied to the collected data where the cognitive load values were the dependent variables, and the AM process was the independent variable. Cognitive load values for each dimension were collectively regressed on the AM process for the analysis. This analysis identified any statistically significant differences in cognitive load experienced between the two conditions. Figure 6 shows the distribution of the cognitive load values for each condition, and Table 3 lists the results from the analysis.

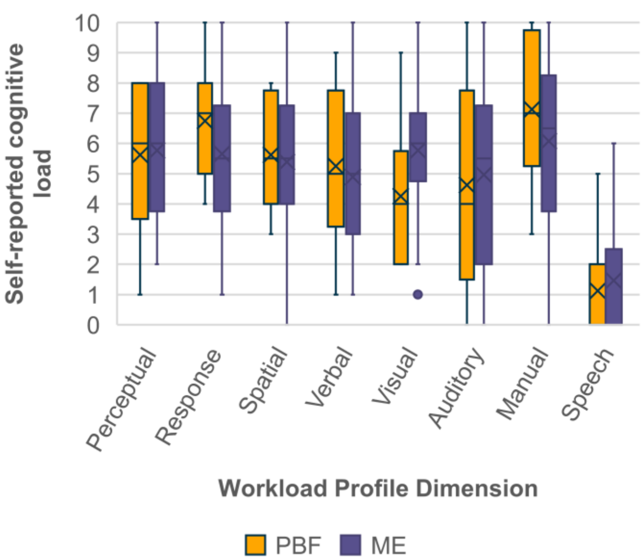


Figure 7: Illustrating the distribution of self-reported cognitive load values for each workload profile dimension.

Linearity was violated when conducting linear regression using the raw data for the visual dimension. This was addressed by removing the outlier (see Figure 7) from the dataset. The results reported are from the linear regression model run after removing the one outlier. From the estimated simple linear regression model in which we regressed the cognitive load values on the centered process condition (PBF= -0.5, ME= 0.5), we observed no statistically significant difference in knowledge gain between both AM process conditions as shown in Table 3.

TABLE 3: Results obtained from linear regression of cognitive load on AM process.

Workload Profile Dimension	Mean		t-value	P-value
	PBF	ME		
Perceptual	5.62	5.77	0.146	0.885
Response	6.75	5.65	-1.133	0.266
Spatial	5.62	5.38	-0.239	0.813
Verbal	5.25	4.88	-0.326	0.747
Visual	4.25	5.77	1.659	0.107
Auditory	4.62	4.96	0.261	0.796
Manual	7.12	6.08	-0.882	0.385
Speech	1.12	1.46	0.411	0.684

6. DISCUSSION

The purpose of conducting two studies was to identify the shortcomings of web performance in CAI and identify testing conditions that focused on the effects of the intervention on knowledge gain and cognitive load. The distribution of the feedback from all 54 participants shown in Figure 8 indicates the quality of the intervention across the two studies.

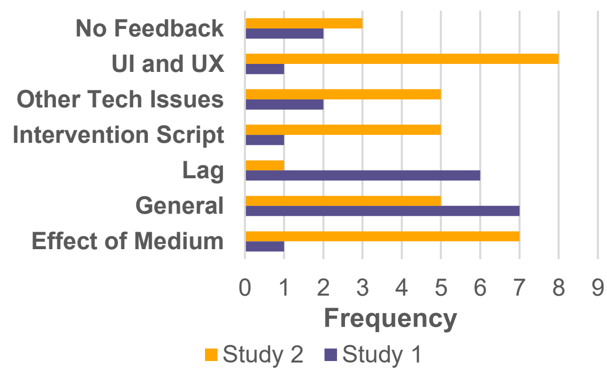


Figure 8: Highlighting the distribution of subjective feedback across the studies.

The comment categories were coded by a single researcher on the team; hence, an inter-rater check was not conducted. General themes regarding the comment topics were identified, and the number of instances of topics was computed. Identical categories were then grouped to concisely and sufficiently describe the types of comments that students made after their experiences. These themes were based on the content of the comments. The themes shown in Figure 3 were as follows:

- **General:** Comments did not mention specific elements while indicating a generally positive or negative experience.
  e.g., "I thought it was great and a very interesting tool to do something like this in chrome."

- **Lag:** Comments explicitly highlighted lag or poor web performance during the experience.
  e.g., "The interactive part was sort of laggy."
- **Other Tech Issues:** Comments highlighted issues not related to web performance but pertained to technical problems such as glitches or bugs during the intervention or screen recording.
  e.g., "In the interactive portion, when I was asked to fill the left side bin with powder, my powder bottle disappeared…."
- **Intervention script:** Comments highlighted issues or problems with the intervention's instructional format.
  e.g., "… I felt like the pauses were a little long between each step and it caused me to feel a little bit disinterested as I went along…"
- **UI & UX:** Comments highlighted the need for visual user interface elements to improve the experience.
  e.g., "Some of the features would be better seen if highlighted some way when explaining what they are and what they do."
- **Effect of medium:** Comments highlighted the characteristic effects observed when learning through an interactive CAI experience.
  e.g., "I found the simulation interesting however, I found it difficult to maneuver the parts in the correct areas."

Comparing the results between the two studies primarily highlights that lower web performance (i.e., due to lag) in the intervention for S1 was a significant concern for participants. We believe that the number of concerns due to lag and low web performance distracted participants from being able to focus on other elements during the intervention. This claim can be supported by the opposite observations in feedback for S2. Participants in S2 were not as concerned with lag as they were with the elements of the intervention. This reduction in lag and improvement in web performance in S2 was attributed to mesh compression of 3D data used in the simulations, elimination of intensive lighting features, and simplification of visual effects. As Figure 8 highlights, participants instead were more concerned with having visual user interface elements in place or were concerned with the challenges of navigating through the computer-aided experience to perform tasks. These findings imply that improvements in web performance from S1 to S2 allowed us to focus on our assessment of knowledge gain and cognitive load purely on the effects of the interventions for each process condition, rather than the shortcomings of the medium.

The goal for preliminary testing in this research was to identify the differences in the knowledge gain and cognitive load experienced when learning about different AM processes through CAI. By validating CAI as an alternate medium to in-person learning, we can improve AM education and offer exposure to the full range of AM processes. Providing this exposure can improve both design- and process-centric AM intuition. Therefore, this research validated an intervention design to improve knowledge in material extrusion and powder bed fusion. The goal behind the intervention was to validate whether designers can gain knowledge for different AM processes and whether they do so while experiencing different levels of difficulty in learning. Our research questions were therefore based on a hypothesis that knowledge gain and cognitive load are affected by the innate process features and user tasks (or actions). These process features can include assembly dynamics, machine terminology, and other forms of functional complexity present in the AM process or AM system. Based on this hypothesis, we designed an intervention script [53] to test our research questions and the findings for the proposed research questions suggested the following:

RQ1. How do the differences between material extrusion and powder bed fusion affect knowledge gain for the AM processes?

The computer-aided intervention significantly affected the knowledge gain for powder bed fusion, which as hypothesized is observed to be the process with lower knowledge as suggested from the lower pre-quiz scores for powder bed fusion than for material extrusion. While participants in both conditions were observed to have performed better on the post-quiz, the difference in knowledge gain between the processes was statistically significantly different. The knowledge gain for the participants in the powder bed fusion process condition was 47.8% higher than the knowledge gain for the participants in the material extrusion condition. We believe that this significant rise in knowledge for the PBF condition was because of the significantly lower prior awareness for the process as was identified as a gap in the literature.

As the results from the regression analysis of awareness and interest and motivation suggested, there was no statistically significant differences between the participants in the two process conditions. This is likely because the participants were recruited from an introductory engineering design class where the general population is primarily novice designers. As a result, they did not have extensive prior experience with AM and were interested and motivated to be introduced to the topic. Therefore, the results from the analysis on knowledge gain showed that any prior awareness participants might have had in AM was biased toward awareness in material extrusion AM. These findings support the gap identified in Section 2 and bolster the need for alternative methods of education. Our findings suggest that CAI of process-centric AM concepts can meet this need and improve process-centric intuition in AM in students. We believe this is because the medium offers an accessible and hands-on opportunity to learn with acceptable fidelity.

RQ2. How do the differences between material extrusion and powder bed fusion affect the cognitive load experienced during learning for the AM processes?

As the results in Table 3 highlight, the effects on knowledge gain, and therefore the improvement in process-centric AM intuition, can be accomplished with no significant difference in cognitive load. This observation refuted our hypothesis for RQ2 as we expected that there might be differences in the perceived complexity of the AM process that would show differences in cognitive load. These observations seem to instead resemble the findings from Starkey et al. [54] that suggest, counter to past literature, that product complexity may not affect cognitive load. Participants reported cognitive load values from the entire experience, therefore there can be underlying effects from the CAI method of education. There is scope for future work to understand whether the reported values were predominantly driven by the virtual medium itself, thereby diminishing the observable effects of the AM process on cognitive load. Furthermore, while these findings on cognitive load suggest that there was no statistically significant difference in cognitive load between the two processes, this research did not analyze the effects of prior stress on the reported cognitive load.

As our secondary hypothesis, we believe that there can be underlying effects added to the cognitive load values reported by the participants due to generally stressful conditions as affected by the COVID pandemic. Although our findings suggest that there was no significant difference in the stress levels for participants before the intervention between the two process conditions, most participants claimed that the listed sources of stress influenced them either about the same or more than they did within the last week. Therefore, we believe that this may have largely affected the generally consistent range of cognitive load values reported by the participants and therefore effects from the intervention may have been too small to observe. There is scope for future work to understand whether the reported values were driven by the reported stress levels, resulting in diminished effects of the AM process on cognitive load.

7. CONCLUSION AND FUTURE WORK

This research analyzed the use of virtual mediums in process-centric learning of AM concepts and selected CAI as the tool of choice. While keeping the current early stages of this work in mind, the preliminary testing in this research still highlighted interesting results with key implications for the future practice of AM education. The results obtained help better understand the observable effects of using a virtual medium, such as CAI, on the quality and effectiveness of the learning experiences. The results also indicate that a significant difference in knowledge gain exists between material extrusion and powder bed fusion. Specifically, students showed a higher knowledge gain in powder bed fusion than they did for material extrusion. The results also highlight that students show no significant difference in cognitive load experienced during learning.

These results imply that the utility of virtual mediums such as CAI can enable AM process-centric education for processes that are typically inaccessible to designers. Education for less accessible processes, such as powder bed fusion, can be provided while not adding significantly more cognitive load to the learning experience when compared to learning about more accessible AM processes such as material extrusion.

There were certain limitations in this research that affected the results obtained during the studies. Knowledge gain in this work was assumed to follow a linear behavior, i.e., a change in knowledge from 0.1 to 0.3 was considered equivalent to a change in knowledge from 0.7 to 0.9. This was because the change in quiz score was associated with knowledge gain and the nature of the quiz and scoring was linear. Future work could consider validating the relationship between knowledge gain and the assessment scores. Regarding the sample of participants, the data collected was limited and unevenly distributed. There is scope to improve the power of the results by collecting data from a larger and more evenly distributed sample of participants. Doing so can indicate the robustness of using virtual mediums for AM education and can therefore contribute to the wider improvement of AM education for design and process-centric education. Furthermore, the work from this paper can be improved by conducting testing with participants who have equivalent prior exposure to AM for all AM processes. There is also scope for future work to develop a stronger designer understanding of AM using other virtual mediums, such as VR. Finally, there is an opportunity to cultivate an understanding of how the medium of education (virtual or in-person, immersive or non-immersive) affects the knowledge gain and cognitive load experienced during learning. Doing so can illustrate the potential in each type of virtual medium allowing us to identify effective solutions for conducting AM education in significant ways to empower the future AM workforce.

8. ACKNOWLEDGMENTS

This research was conducted through the support of the National Science Foundation under Grant No. 2021267. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the NSF. We would also like to thank Dr. Stephanie Cutler for her guidance and advice, and Xact Metal for providing the 3D data for their powder bed fusion machine, and for their continued assistance with this research initiative.

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