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THE ROLE OF IMMERSIVE VIRTUAL REALITY IN DEVELOPING DESIGN AND PROCESS INTUITION FOR ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) is poised to empower industries with sustainable, low-cost, and rapid solutions to market. However, the wide adoption of AM technologies is inhibited by the deficit of skilled engineers who can design for AM (DfAM) and innovate with AM. As such, there is a need to develop resources that can help students and professionals develop the necessary intuition for DfAM and AM processes. For this purpose, this research investigates the role of immersive virtual reality (VR) in developing design and process intuition for AM. The initiative divides efforts into three topics: 1. AM process training, 2. DfAM education, and (3) problem-solving with AM.

First, this research investigates the role of immersive VR in instructing students about two AM processes: PBF and material extrusion (ME). The research compares the effectiveness of immersive VR, computer-aided instruction (CAI), and real-world (REAL) experiences. Evidence from this research indicates how VR serves as an alternative to in-person training to improve acquiring AM process competency. Findings showed that the differences in immersion and presence between CAI, VR, and in-person instruction do not have a statistically significant effect when learning about ME, but do have a significant effect when learning about PBF. Specifically, VR generally yields equivalent effects in knowledge gain and cognitive load to in-person PBF education while offering advantages in both metrics over CAI learning.

Second, this research investigates the role of immersive VR in developing DfAM intuition. Again, the research compares the effectiveness of immersive VR, computer-aided education (CAE), and REAL experiences. The evidence collected has interesting implications for how organizations train designers in DfAM and the role of immersive modalities in design processes. Findings indicated that the outcomes from DfAM evaluations in immersive and non-immersive modalities are similar without statistically observable differences in the cognitive load experienced during the evaluations. Active engagement with the designs, however, was

observed to be significantly different between immersive and non-immersive modalities. By contrast, passive engagement remained similar across the modalities.

Third, this research investigates the role of immersive VR in problem-solving with AM. The research compares the effectiveness of immersive VR and computer-aided (CAx) experiences in solving a design challenge with AM. Insight derived from the evidence informs on how future designers must be trained in DfAM problem-solving to meet the AM demands in the workforce. Specifically, insight into the potential of immersive environments to influence change in the manufacturability outcomes of 3D printed parts. Results showed that participants in VR yielded significantly different outcomes to problem-solving with AM when working with fundamentally complex designs. In other words, the VR condition when compared to the CAx condition yielded a significantly higher increase in DfAM score, and a decrease in print completion time and support material usage.

These investigations provide new knowledge on how immersion in VR affects learning about AM processes, DfAM education, and problem-solving with AM. Upon connecting the different investigations, findings demonstrate a relationship between process-centric considerations and the influence of immersion. Additionally, higher active engagement with the designs also does not seem to correlate with better outcomes in DfAM and 3D printing processes. Furthermore, the interdependence between DfAM and AM process factors plays a key role in how designers benefit from immersive experiences. Summarizing this knowledge yields a new framework for designing immersive VR experiences for AM and DfAM contexts. This framework connects the findings from the three topics and offers new insights into the role of immersive VR in developing design and process intuition for AM. In conclusion, this research presents transformative insight into the future of AM workforce development, expanding upon existing AM literature, and opening new opportunities for research and practice in AM and DfAM education.

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To Eren, the real first author

All this would not have been possible without your unwavering love and encouragement

Chapter 1

INTRODUCTION

1.1. THE NEED FOR AM WORKFORCE DEVELOPMENT

Global engineering challenges have forced industries to seek innovative solutions to improve product development and manufacturing processes. Sustainability, cost, and time-to-market pressures have led to the adoption of advanced manufacturing technologies, such as additive manufacturing (AM), to address these challenges. Additive manufacturing is the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [1]. This means end-use parts produced with AM incorporate unique geometric and material complexity, making them distinct from parts created by these other manufacturing methods [2,3]. Although there is a high demand for AM as a result, wide adoption is lacking due to a skilled AM workforce shortage [4,5]. Solving problems with AM requires competency in working with a range of AM processes [6–8] and possessing the design for additive manufacturing (DfAM) intuition to think *generatively* [9,10]. This means that organizations must invest in training their workforce with the design and process-centric AM knowledge they need to solve problems with AM [11–13]. Since DfAM intuition refers to the designer's ability to evaluate and modify designs for manufacturability by AM, designers must actively experience the benefits and limitations of AM to comprehend how they affect the fabricated output [14]. Such experiences help produce innovative solutions and minimize failures, defects, and functional errors during product realization [3,15]. To help acquire DfAM intuition, resources must be developed to instruct designers on AM processes and their DfAM considerations. Such developments necessitate an investigation into how design and process-centric AM concepts must be communicated to designers to foster DfAM intuition and problem-solving skills. The research presented in this document was motivated by the need for this investigation, presenting new insight into how the modality of instruction affects DfAM and AM process learning.

1.2. THE ROLE OF IMMERSIVE VR IN AM AND DFAM

Industries have been quick to adopt metal AM technologies, such as powder bed fusion (PBF), to produce complex and lightweight parts for aerospace, automotive, and medical applications [16–19]. Leveraging AM in end-use applications, therefore, requires organizations to train their workforce on designing and fabricating parts for processes like PBF. However, such AM processes are complex and often dangerous to operate, making it difficult for designers to learn about them in a hands-on manner. Investing in proper infrastructure ensures safe operating environments [12,13] or relying on computer-aided learning and interaction [20,21] are common solutions to this problem. However, the former is expensive for smaller organizations and institutions making hands-on engagement inaccessible, and the latter is limited in its medium of presentation and utility. Active and hands-on learning and design decision-making are essential for honing one's design intuition [22–24]. This means when in-person, physical, learning and interaction are not possible, designers must use a digitally immersive modality as an alternative. As shown in Figure 1.1, this is where virtual reality (VR) comes into play.

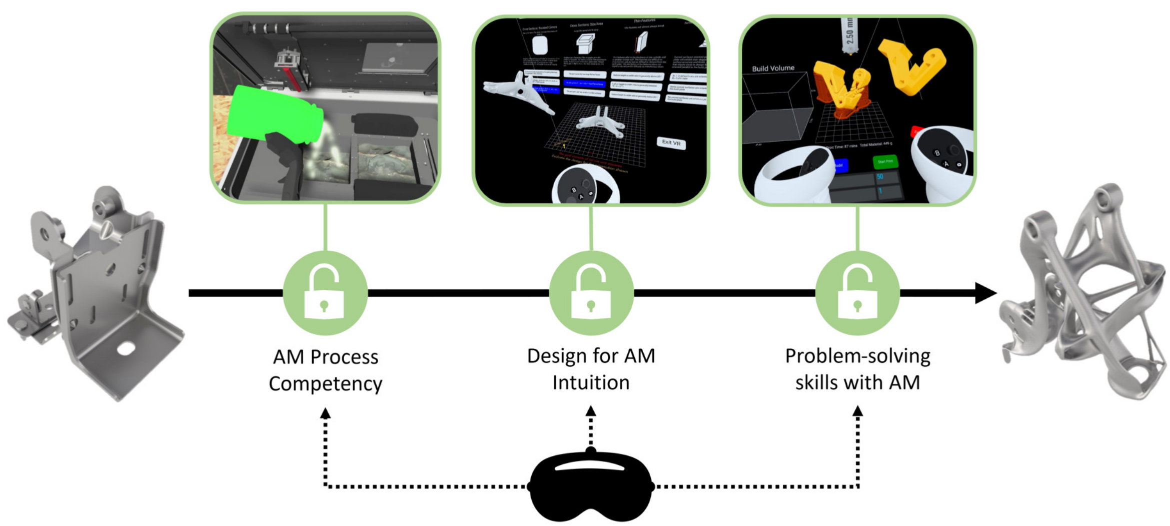


Figure 1.1: Demonstrating the use of VR to support AM adoption by enabling AM process education and the development of DfAM intuition and problem-solving skills

Unlike traditional computer-aided technologies (CAx), often on flat, digitally non-immersive, screens, VR provides a digitally immersive environment that can simulate physical experiences and interactions [25–27]. There is evidence to therefore suggest VR's potential to foster active learning and problem-solving experiences for AM without incurring the costs of physical infrastructure. Such potential merits an investigation into the specific use of VR for AM and DfAM applications. The research in this document highlights this investigation for AM processes like material extrusion (ME) and PBF in VR, demonstrating VR's potential for hands-on AM training.

Solving problems with AM also requires designers to make mission-critical design decisions on an artifact's manufacturability. Such decisions particularly play a crucial role in early-stage design processes where prototyping and artifact generation are essential steps [28,29], and where the cost of failure is low [30]. However, such decisions are significantly influenced by the environment in which they occur and the resources that are made available to the designer. This means that the environment in which designers make these decisions can significantly impact the quality of the end product [31–33]. For AM purposes, this means that the environment in which designers design and evaluate their ideas for AM can significantly impact the quality of the fabricated output. The digital 3D nature of design demands intuitive 3D environments inside which designers can engage seamlessly with their artifacts. Virtual reality can satisfy this need as illustrated in Figure 1.1.

In addition to offering safe environments to work with AM systems, digital immersion in VR impacts spatial reasoning, perception, recall, and decision-making thereby affecting design processes. Engaging in VR also improves the acquisition of declarative and procedural knowledge and cognitive and affective skills. This further influences memory recall, affecting the application of such knowledge and skills. As designers learn about AM processes in VR, it is essential to understand how they also think about and process their inherent DfAM considerations in VR. As such, understanding how the differences between non-immersive CAx and immersive VR environments affect design evaluation and decision-making is essential. Given the nature of geometric complexity AM parts distinctly incorporate [2,3], there is a need to identify design modalities for AM that best spatially inhabit such complexity. This research investigates the evaluation of designs in VR for 3D printability, studying how immersion affects engagement with the design, experienced cognitive load, and the outcomes of the evaluation.

1.3. SUMMARY OF THE STUDIES CONDUCTED

The research presented in this document is motivated by the need to empower designers with the knowledge and skills necessary to solve problems with AM. Specifically, the investigation identifies the role of immersive modalities in AM and DfAM applications, as an alternative to in-person and non-immersive CAx experiences. As a result, this research establishes a new domain of knowledge based on observed evidence on the effects of immersion on AM and DfAM experiences. As shown in Figure 1.1, the research carried out in this document works on advancing knowledge in three key topics: 1. AM process education, 2. honing DfAM intuition, and fostering problem-solving skills with AM. Evidence from research into each topic is presented in this document, offering insight into the effects of immersion on AM and DfAM experiences. This evidence is also distributed in the following papers:

1. Mathur, J., Miller, S.R., Simpson, T.W., & Meisel, N.A. (2023). Designing immersive experiences in virtual reality for design for additive manufacturing training. *Additive Manufacturing.* doi: 10.1016/j.addma.2023.103875

This published paper contributes new knowledge on the design of VR experiences for AM and DfAM applications (see Chapter 3). Specifically, it addresses the lack of information on design guides for creating immersive experiences that can support these research endeavors. Evidence from the work establishes guidance on designing immersive experiences to support the development of experiences that cultivate DfAM intuition, AM process competency, and problem-solving skills.

2. Mathur, J., Miller, S.R., Simpson, T.W., & Meisel, N.A. (2023). Effects of immersion on knowledge gain and cognitive load in additive manufacturing process education. *3D Printing and Additive Manufacturing.* doi: 10.1089/3dp.2022.0180

This published research offers insight into the effects of immersion on AM process learning for different AM processes (see Chapter 4). Specifically, the research evaluated the use of CAI, VR, and in-person instruction in AM process education when learning about material extrusion (ME) and PBF. The evidence from this research indicates how VR serves as an alternative to in-person training to improve acquiring AM process competency.

3. Mathur, J., Miller, S.R., Simpson, T.W., & Meisel, N.A. (2024). A mixed-methods investigation of how digital immersion affects design for additive manufacturing evaluations. *Journal of Mechanical Design.* (in review, preliminary work presented at a prior conference doi: 10.1115/detc2022-90063)

This paper investigated how varying levels of immersion affect DfAM evaluation experiences (see Chapter 5). It contributes new knowledge on the effects on the outcomes of the DfAM evaluation, the effort required of evaluators, and their engagement with the designs. The evidence collected has interesting implications on how organizations train designers in DfAM, as well as on the role of immersive modalities in design processes.

4. Mathur, J., Miller, S.R., Simpson, T.W., & Meisel, N.A. (2024). Studying changes to the additive manufacturability of design solutions when prepared and simulated in immersive virtual reality. *50th Design Automation Conference (DAC)* and *Additive Manufacturing.* (in preparation for both)

This research investigates the effects of immersion on DfAM problem-solving outcomes (see Chapter 6). It contributes new knowledge on the effects of immersion on the 3D printability outcomes of designed artifacts when determining the ideal print orientation. Insight derived from the evidence informs on how future designers must be trained in DfAM problem-solving to meet the AM demands in the workforce. Specifically, insight into the potential of immersive environments to influence change in the manufacturability outcomes of 3D printed parts.

1.4. DOCUMENT OVERVIEW

This document first reviews support from literature in Chapter 2. The literature review explains the current state of the art in the field and identifies gaps in the addressed by this research. This includes a discussion on the gap in AM and DfAM learning literature, the state of the art in immersive technologies, and the need for VR-based training in AM and DfAM. Chapter 3 then describes the framework used in this research to investigate VR-based training for AM applications. The framework emphasizes the importance of design for VR and mapping

DfVR to AM concepts to communicate 1. knowledge of AM processes, 2. knowledge on DfAM, and 3. knowledge in AM problem-solving. Diving into this framework, Chapter 4 provides knowledge from an investigation of VR-based training for AM process training. Specifically, the chapter informs on the effects of immersion on knowledge gain and cognitive load from process-centric AM learning. Next, Chapter 5 adds to this knowledge by informing on the effects of immersion on DfAM reasoning during artifact evaluations for 3D printability. The chapter describes a mixed-methods investigation that sheds light on the effects of immersion on DfAM evaluation outcomes and designer engagement in different environments. Chapter 6 combines the learnings from the previous chapters to inform on the effects of immersion on DfAM problem-solving outcomes. Specifically, the chapter elaborates on the effects of immersion on how designers create and evaluate artifacts for 3D printability. The investigation forces designers to consider both design and process-centric AM concepts simultaneously with the help of a virtual 3D printer. Lastly, Chapter 7 summarizes the collective knowledge from the work, identifies the key implications, intellectual merit, and broader impact of the work, and offers concluding remarks.

Chapter 2

LITERATURE REVIEW

Organizations looking to onboard AM talent alongside their existing domain expertise require designers who understand the benefits and limitations of the technology. More importantly, they need designers who can apply this knowledge to solve engineering problems with AM. The digital 3D nature of AM suggests an intuitive need for 3D environments inside which designers can engage with seamlessly inherited 3D artifacts. Virtual reality makes intuitive sense to investigate as the modality to present environments for active learning and experiential design with AM. The following review of past literature supports this investigation into VR-powered experiences for AM. Section 2.1 elaborates on the benefits of active instruction and emphasizes the need to incorporate these in immersive experiences. Section 2.2 compares and contrasts immersive and non-immersive modalities to identify the effects of enhanced digital immersion on user experiences. Next, Section 2.3 identifies the gap in AM literature surrounding immersive training experiences and motivates the need to design and investigate such experiences. Finally, Section 2.4 elaborates on the need to investigate the use of virtual manufacturing in VR to simulate problem-solving with AM.

2.1. THE NEED FOR ACTIVE INSTRUCTION TAILORED FOR AM AND VR

Designers have to constantly process new knowledge to make informed decisions during design processes. As such, how they learn and acquire knowledge strongly influences how they solve problems. When solving problems with technologies like AM, acquiring technical and methodological competencies with the technology is vital [14,34]. This requires them to actively experience the benefits and limitations of such technologies to gain these competencies [14,35] Doing so enables them to intuitively parse through different dimensions of the problem-relevant knowledge to create unique solutions [36,37]. Therefore, design and engineering processes must incorporate meaningful experiential learning over traditional rote learning [38,39]. Inductive teaching methods, such as active learning, have been historically used to meet this purpose in STEM domains [24,40–44]. They offer an improved understanding of concepts and ideas compared to traditional instruction techniques [45,46]. Such benefits are essential to developing a skilled engineering workforce for AM [47,48]. This warrants an investigation into incorporating active instruction in DfAM and AM process training.

Higher education in design, engineering, and manufacturing leverages problem-based active learning to enforce concepts and promote critical thinking [22–24,43,49]. In other words, individuals experience *dynamic* problem-solving to *build upon* their knowledge rather than *acquire* it [46,50,51]. This approach promotes a *construction of knowledge* from an experiential and introspective understanding of the world [52,53]. However, careful consideration must be given to the fundamental assumptions behind the instruction of knowledge with such an approach. Specifically, the instructional design to support one set of learning objectives may not apply to another set of objectives [54]. This means that the assumptions behind offering instructional feedback to support traditional DfM must be reconsidered for DfAM objectives. Similarly, non-immersive DfM instructional practices must also be reassessed on their role in DfAM instruction with immersive VR. This collective work will identify the effects of the presentation of information on learning [31]; specifically, on the learners' knowledge and experiential cognitive processing [55]. As a result, this research is motivated to investigate the instructional design of immersive experiences for DfAM and AM process training.

2.2. IMPLICATIONS OF ENHANCED IMMERSION ON USER EXPERIENCES

Digital modalities can provide engaging active learning experiences that are identical to in-person experiences [56]. Organizations have historically used non-immersive computer-aided experiences for this purpose. This includes leveraging CAx-driven game-based [56–58] or simulation-based [59–62] design and manufacturing experiences. Such experiences challenge users to reflect on the impact of their decisions, fostering technical and professional skills [59]. Additionally, they improve collaborative learning from problem-solving situations [63], improve performance with procedural goals [57], and induce high states of concentration, engagement, and satisfaction at low cognitive loads [58]. Immersive VR, however, builds upon conventional CAx experiences by enabling improved design conceptualization and analysis [64]. Added immersion and presence strongly influences the 3D perception of designs [65,66] and other presented information [31]. When compared to physical and CAx modalities, engagement from immersive VR is shown to bolster creativity [67] and design concept generation [68]. Similar trends are observed when compared to passive and non-immersive video-based experiences. Specifically, engaging in VR yields higher enjoyment and improved learning outcomes [69] and higher and sustained levels of self-efficacy [70] when compared to video-based learning. Engaging in VR also improves the acquisition of declarative and procedural knowledge [25] and cognitive and affective skills [26]. This further influences memory recall, affecting the application of such knowledge and skills [71].

Literature encourages the use of immersive modalities for DfAM and AM process training, often by contrasting their benefits over non-immersive modalities. However, the broader effects of VR engagement continue to be debated and must be considered. Past work identifies the mixed effects of VR engagement in science and education due to environmental factors [27,72–75]. Specifically, it emphasizes that the environmental and pedagogical conditions of the designed immersive experiences strongly influence meaningful outcomes [76–82]. The observed cognitive load is similarly influenced by the manual operations required by the environment during design and learning experiences [83–88]. This diversity of evidence reinforces the need to closely study the use of VR in DfAM and AM process training environments. Specifically, effects on spatial perception and reasoning and the user's psychomotor abilities [32] and the experienced cognitive load must be examined [33,89] in problem-solving situations.

2.3. THE LACK OF IMMERSIVE AM AND DFAM PROBLEM-SOLVING

Relying on modern DfM principles during design encourages designers to check their intuition on a design's manufacturability. It is important to note, however, that the task of visually evaluating designs for manufacturability is best suited for early-stage problem-solving. This is because the cost of rework is low at this stage, and the designer's *tacit knowledge* on

DfAM is poised to promote innovation [30]. Using automated analysis tools is better suited for the end stages of the design process [90], where the cost of rework is high. As a result, practicing DfM with early-stage designs reduces development time and cost, and increases performance, quality, and profitability [3,15]. Resources for DfM are therefore widely available to help designers practice DfM during design processes. Design for AM guidance, however, is not widely incorporated in these DfM resources. This is because the layer-by-layer additive process invokes *generative* and *organic* design thinking [9,10]; a departure from the subtractive design thinking invoked with several other manufacturing processes [2,3]. Designers need access to DfAM principles in addition to DfM principles during design processes. As a result, different worksheets [91–94], methodologies [7,95], and design heuristics [96,97] help fill in lacking DfAM knowledge. However, these resources are limited to utility and comprehension in non-immersive modalities. Limited work investigates alternate modes of presenting designers with DfAM knowledge [98,99]. There is a gap in the literature that examines how differences in immersion between modalities influence DfAM consideration. Immersive experiences for AM must be designed to support such an investigation, but this requires knowing how to design such experiences.

Literature advocates for problem-based and task-based instructional designs in DfAM and AM process training respectively. Frameworks that leverage such active instruction help cultivate student understanding of AM processes and their DfAM considerations [100,101]. They increase motivation and engagement, improve communication and oral presentation skills on AM concepts [102], and impact design creativity [103,104]. However, such past work inherits the non-immersive instructional practices historically used for traditional manufacturing technologies [105]. Research indicates that adding VR immersion promotes improved capabilities in manufacturing and assembly conditions [106,107]. Immersive VR also enables designers to better perceive the dimensional fit of a design [108,109]. Compared to CAx evaluations, this enhanced perception improves the ability to identify errors and defects with 3D models [110,111]. Additive manufacturing technologies operate with digital data that intuitively fits inside digital environments like VR. Literature also encourages using VR to cultivate domain-relevant knowledge and competencies in design and engineering. Therefore, leveraging

VR for DfAM and AM process training and problem-solving merits further investigation.

2.4. PROBLEM-SOLVING WITH IMMERSIVE VIRTUALIZED AM

It is important to distinguish experiences designed to foster problem-solving capabilities with AM from those designed to impart knowledge or provide training on AM and DfAM. The former requires the designer to research information and apply knowledge and skills to develop solutions to a defined problem [112,113]. The latter requires designers to *learn by doing* with instructional guidance, focusing on the acquisition and transfer of knowledge [112,114]. This means that the role of the instructional guidance that is offered to designers is different in each case. Specifically, guidance for problem-solving acts as feedback to the designer's actions in their attempts to research and identify solutions. While guidance for imparting knowledge or training acts as a scaffold to the designer's learning process. As such, visualizing a solution and gathering feedback on its viability is a crucial step during problem-solving. This is especially true for AM, where the designer must visualize the impact of the AM process on the manufacturability of their designs to solve design problems [115].

Designers have historically relied on non-immersive virtual simulations to obtain feedback on their designs [116,117]. However, using VR to obtain design feedback demonstrates the potential for improved learning and communication outcomes, key requirements for effective problem-solving [118–121]. Openness to the use of VR further promotes its effectiveness [122] and leads to enhanced engineering design creativity [123]. As a result, problem-solving in VR yields favorable outcomes in environments that are simulated to mimic real-world conditions [124–126], or designed to inform on actions to take in real-world situations [127–129]. The field of manufacturing and design, therefore, stands to benefit from similar uses of VR. Specifically, experiences in VR that are designed to provide virtualized manufacturing feedback on designs can significantly improve the problem-solving capabilities of designers. There is therefore merit in investigating the use of VR for problem-solving with AM.

Problem-solving with AM requires experiences with 3D printers that are driven by a functional context [115]. This means that designers must visualize their solutions to assess their feasibility and effectiveness while receiving manufacturing feedback on their designs. While physical prototyping is a common practice to visualize and test designs, it is impractical due to the high cost and time required to produce parts [130,131]. That is, receiving contextual feedback from visualizing the real-time physical fabrication is slow and runs the risk of being expensive due to failures. As such, *virtual manufacturing* methods, such as computer simulations, data models, and other digitally fabricated resources, help visualize and test products and manufacturing processes before their physical realization [132–134]. While CAx environments are widely used for this purpose, immersive VR further improves design conceptualization and analysis [64] demanding simulated AM environments in VR [135,136]. This means that virtualized AM processes must be integrated into immersive VR experiences to enhance AM and DfAM problem-solving. Specifically, designers must receive feedback from the simulated building of their part, similar to the visuals offered by standard slicing and print preparation software. Watching how their design materializes will help visualize the impact of the AM process on the manufacturability of their designs. Past work in virtualized AM shows potential in demonstrating the 3D printing outcomes of different designs to offer such insight [60,137,138]. However, such work lacks a design problem with a functional context where designers must create and evaluate their designs for 3D printability in various print orientations. Such circumstances must be studied further to understand how immersion affects a designer's evaluation of their designs for manufacturability with AM during problem-solving.

Chapter 3

CREATING VR EXPERIENCES FOR AM

3.1. INTRODUCTION

Designers use prototypes (or artifacts) to quickly check their designs and communicate their ideas. These prototypes can be digital or physical, often as sketches, 3D models, or physical props. Actualizing designs through such prototypes promotes informed decision-making during design processes [28]. Exposure to one's designs through representations can further adjust a designer's mental models [139], boosting design performance [29]. Working with digital and physical prototypes is, therefore, of paramount importance to solve design problems. However, extensively using traditionally manufactured physical prototypes can be expensive and time-consuming [130,131]. This delays the delivery of end-use products and increases the overall cost of the design process. Using additive manufacturing (AM) can reduce the time and cost of physical prototyping. Expertise in designing for AM is, therefore, a prerequisite to using AM for prototyping. However, few designers possess this design for additive manufacturing (DfAM) expertise [4,5,140,141], inhibiting them from leveraging its advantages. Designers must be trained on DfAM to take advantage of AM during design processes. The dependency of the physical AM artifact on its digital source [130], however, necessitates that such DfAM training happens early in the digital design phase [104,142]. Doing so will equip designers with the intuition to make design decisions that minimize defects and build failures. Instilling designers with such DfAM intuition is, therefore, essential to the quick development of end-use products.

Design for AM considerations typically deviate from the common design for manufacturing (DfM) considerations, requiring separate expertise on designing with AM [3,8]. Design teams looking to benefit from AM in early-stage artifact generation are, therefore, inhibited by the lack of domain knowledge within organizations [12,13]. Overcoming this knowledge deficit is crucial to empowering organizations with the talent to innovate with AM [11]. Acquiring DfAM intuition on the full range of AM processes first requires designers to gain technical competency working with 3D printers for each process [6–8]. However, barriers to physical access to complex AM processes inhibit designers from gaining such technical competency. For processes like powder bed fusion (PBF), these barriers include the cost, safety, and infrastructural requirements involved with running and maintaining the printers [20,21,143]. Designers must actively experience the benefits and limitations of emerging AM technologies to solve engineering problems with them [14,34,35]. The challenges associated with gaining in-person hands-on engagement with AM technologies, therefore, necessitate the need for digitally accessible experiences. Virtual interaction with 3D printers of different AM processes will provide designers the opportunity to intuit their DfAM considerations to apply in artifact generation.

Introducing key DfAM and AM process concepts in a functional context using intuitive experiences with 3D printers is critical to improving artifact generation during design processes [115]. Since physical access to 3D printers is limited, designers must be trained on these concepts using digital experiences. Therefore, digital AM systems must replicate exposure to the functional composition of the technology and illustrate the 3D printing of a designed artifact. Science and engineering have historically leveraged simulations, games, and digital twins using computer-aided technologies (CAx) for this purpose [61,62,144,145]. They quickly garnered interest in various applications due to the observable enhancement of different learning outcomes [146,147]. Although such digitally non-immersive experiences can also be used for AM education [60,148], research recommends modalities with enhanced immersion for this need instead. This is because modalities with enhanced immersion and presence influence 3D perception [65] to improve design and engineering experiences and their experiential outcomes [106,107,110,111,149]. Past work even shows promise in specifically teaching design and process-centric AM concepts using virtual reality (VR) [99,137,138,148]. However, limited research in AM investigates how differences in immersion between digital and physical modalities affect process learning [148], applying DfAM [99], or artifact generation in a functional problem-solving context. This gap in the AM literature necessitates a comparison of immersive and non-immersive modalities to in-person experiences in design and process-centric AM training.

Immersive and non-immersive experiences with AM, such as those offered by VR headsets and flat-screen computers respectively, must be compared to their physical counterpart. Although the literature supports this investigation, no known work establishes how experiences in VR must be designed for AM purposes. Therefore, a review of the literature on the design of digital experiences across the varying levels of immersion is required. This knowledge will inform the design of immersive experiences for AM for this research, and the development of AM-focused training programs and curricula. The goal of this work is to, therefore, study the design of immersive VR experiences for AM and present a generalized framework for designing such experiences. For this purpose, Section 3.2 proposes a generalized framework, informing the design of immersive experiences for AM. Section 3.3 presents a sample VR experience using the proposed framework for problem-solving and artifact generation with AM. Lastly, Section 3.4 summarizes the collective contributions of this work and its limitations, and proposes needs for future work.

3.2. DESIGNING IMMERSIVE EXPERIENCES FOR AM

Additive manufacturing knowledge is broadly classified under design or process-related topics (see Figure **??**). Designers must become experts in these topics for the range of industrial AM processes. To competently design artifacts for AM in industrial product design processes, designers require:

1. *Knowledge of AM processes*: AM process types and their capabilities and limitations
2. *Knowledge on DfAM*: Design guidelines and heuristics derived from process characteristics
3. *Knowledge in AM problem-solving*: Applying DfAM in problem-solving for new or re-designed artifacts

Process and design-centric AM knowledge must be acquired through active engagement with AM systems and DfAM tools respectively. Developing problem-solving skills with AM requires doing both simultaneously while receiving simulated feedback, specifically from the 3D printing of a designed artifact. Such engagement will develop critical thinking and problem-solving skills that are applicable in the physical world (see Section 2.1). To promote active engagement with AM, this work presents a generalized framework for designing immersive VR experiences in Figure **??**. This framework provides the basic conceptual architecture for designing VR experiences for AM applications. It was constructed after studying over 300 designers who were introduced to AM in VR during previous work by the authors [99,148]. The goal of the framework is to promote procedural and declarative knowledge acquisition using task-based and problem-based engagement with AM. This section elaborates on how it elicits acquiring such knowledge on AM and DfAM concepts to cultivate cognitive skills in problem-solving with AM. However, before diving into this section, it is important to understand the role of procedural and declarative knowledge in DfAM and AM process training.

Procedural knowledge is the knowledge of performing a specific task or cultivating a hands-on skill. It is essential when operating or calibrating AM systems and their components, and understanding their functional impact on fabrication outcomes. This means that cultivating knowledge of AM processes is strongly dependent on procedural knowledge acquisition. Figure **??** illustrates how task-based engagement with deconstructed AM process concepts can provide this knowledge. Declarative knowledge is the knowledge of what something is and is often acquired through reading and listening. Context derived from verbal, auditory, and visual cues falls under this category of declarative knowledge. These cues can include a digital assistant providing audio feedback or a text box that highlights engineering information. Processing such declarative knowledge is crucial to stimulate perception and reasoning for improved decision-making. This means applying knowledge on DfAM and assessing AM process effects is dependent on declarative knowledge acquisition. Figure **??** illustrates how problem-based engagement with 3D artifacts and DfAM feedback can provide this knowledge. The goal of this research is to design and study the use of immersive VR experiences that cultivate DfAM intuition and AM process competency. Such design intuition and technical competency can be fostered by acquiring procedural and declarative knowledge from AM and DfAM instruction. How designers acquire this knowledge, therefore, plays a pivotal role in their developing expertise in AM artifact generation.

Immersive VR experiences are strongly positioned to cultivate AM expertise through procedural and declarative knowledge acquisition. As a result, the proposed framework in

Figure **??** bridges key AM concepts and DfVR heuristics from the literature (see Section 3.2.1). Section 3.2.2 emphasizes the need to prepare designers for immersive experiences by providing tutorials on using VR. Though not a part of the proposed framework, this is a prerequisite to working with VR experiences on AM. Implementing a *ramp-up* period ensures that designers can focus on learning AM concepts and not on learning how to use VR. Following this, Sections 3.2.3, 3.2.4, and 3.2.5 discuss using the framework to instruct knowledge on AM processes, DfAM, and AM problem-solving respectively.

3.2.1. Design for VR considerations for AM experiences

Experiences for AM in VR must tailor instruction to industrial requirements Not doing so may render VR experiences ineffective in imparting AM knowledge and skills [150]. This means requires an understanding of 1. design for VR and 2. DfAM and AM process knowledge. First, designers of VR experiences must understand how adding digital immersion and presence influences a user's experience. Intuitively, they may consider reusing established strategies on human-computer interaction from non-immersive game-based experiences [151,152]. However, these strategies can be challenging to apply due to hardware and software limitations [153]. Therefore, acquiring DfVR intuition highlights the importance of using heuristics for immersive experiences over those for non-immersive experiences. This means that VR experience designers must first grasp the concepts of digital immersion and presence. Then they must understand their role in the DfVR heuristics found in the literature.

Digital immersion and presence are the extent to which the environment can mimic visual, auditory, and other sensory elements of the physical reality [25,26,154]. As a result, immersion and presence dictate how compelling, engaging, and educationally meaningful the VR experiences are perceived [76,155,156]. Though the two are distinct concepts, this presented work may use the term *immersion* to refer to both. This is to retain focus on the main topics and improve the clarity and readability of this work. Design for VR, therefore, is the process of strategically leveraging digital immersion to achieve specific experiential outcomes. The following heuristics elaborate on adopting human-centered DfVR considerations:

- *Simplifying the contextual geometry*

  Using basic geometries with consistent scaling and including familiar objects with standard sizes is essential [157]. This is vital in design for manufacturing as the size, form, and fit of the designed features must be easy to contextualize. For this purpose, the VR controllers themselves can offer context to intuit the scale and form of an imported artifact.

- *Making aesthetics and realism secondary*

  Ease of use and comprehension should be prioritized, primarily by limiting high-resolution realism to prevent cognitive overload and fatigue [33,158]. Specifically, by incrementally adopting photorealistic textures, lighting, shadows, and body accuracy on human avatars, engrossing users inside simple yet natural surroundings [159]. Doing so maintains focus on the essentials, minimizing uncontrolled effects due to environmental novelty or discomfort while promoting inclusive and universal design [160].

- *Using intuitive mapping to the physical world*

  Apply human-centered design to simplify the user's mental models on interactions in VR and minimize experiential cognitive load [31,33,153]. To do so, consider consistent and unambiguous signifiers and introduce guides and mappings with informative and comprehensive feedback. Doing so *encapsulates* users with content for intuitive and interactive knowledge gain [161], promoting informed decision-making.

- *Balancing realism with direct and indirect interactions*

  Incorporate realistic interactions that are naturally expected by users. For this purpose, selectively use indirect interactions when direct interactions are nonessential to minimize fatigue and experiential cognitive load [157]. Doing so can increase meaningful engagement with the experience and promote skill development [155,156]

Although not a comprehensive list, these heuristics were identified to be most relevant for AM experiences. A key takeaway from the identified DfVR heuristics connects to the second expertise requirement: having DfAM and AM process knowledge. This expertise is required to package key DfAM and AM process concepts onto VR elements for intuitive instruction. This means that designers must first establish functional breakdowns of the different design [91,92] and process-centric [162] concepts in AM. They should then consider different types of sensory information to map and communicate the different AM concepts [157,158]. The sensory elements in VR must actively guide designers in applying DfAM considerations in product design processes [100,102,104,163]. Past DfAM tools such as worksheets [91,92], cards [97], and flowcharts [162] illustrate the successful mapping of AM concepts to visually comprehensible information. Such strategic mapping must be replicated using the identified DfVR heuristics to design immersive experiences for AM.

3.2.2. Use tutorials to prepare users for VR experiences

Data collected from previous work by the authors in 2022 (shown in Figure 3.2) demonstrates the need for *user prep time*. Specifically, it shows that designers are more familiar with using CAx tools than VR tools when working with 3D models.

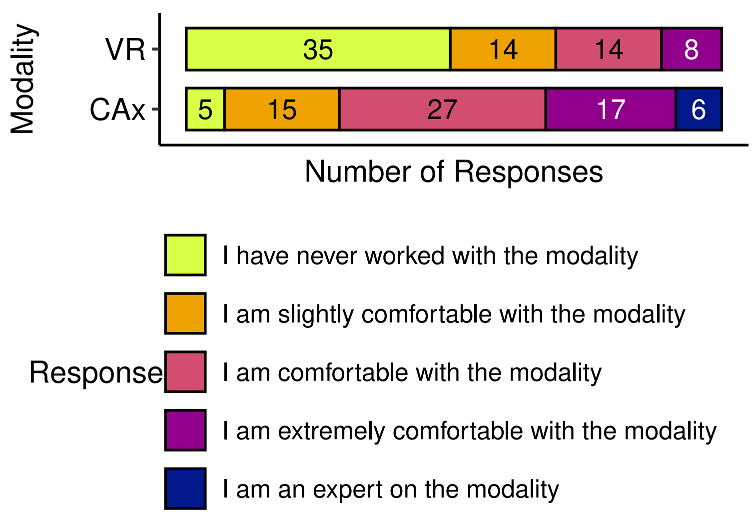


Figure 3.2: Highlighting the difference of expertise in interacting with 3D models between CAx and VR tools

Note that the sample in this dataset is a group of second and third-year engineering students at an R1 university. Therefore, this trend is likely observed because of the prior curricular training in computer-aided design (CAD) the students would have received. However, they may not have had any formal exposure to VR. This observation is not surprising; however, it is important to note that the lack of experience with VR can be a barrier to using VR for AM. This demands the need for training specifically in VR as a prerequisite to using VR for AM. Specifically, using a tutorial or practice session that replicates the intended AM experience. Users must adapt to the new forms of visual, auditory, and haptic information they receive and practice executing motor movements in VR. Such practice is especially important as the medium can be overwhelming and distracting for users [157,158] and the lack of physical feedback can be disorienting [26,154]. Figure **??** shows the key elements of a VR experience where tutorials can help account for the disparity between CAx and VR expertise.

Timed tutorials about using VR must be designed such that users perform tasks and complete goals to understand the capabilities of their environment. Such tasks could include 1. reading or listening to declared information, 2. interacting with user interface (UI) elements such as buttons, picking up and moving 3D objects, and 3. traveling (walking or teleporting) within a bounded space. Taking an example relevant to AM, Figure **??** presents a tutorial to undergo prior to any AM process-centric learning. As shown in Figure **??**, users undergoing AM process training are expected to interact with components on an AM system. They must understand how the components help 3D print parts to intuit the effects of the process on the artifact. As such, the tutorial must instruct on moving within the VR space (i.e., walking or teleporting) and manipulating objects in the environment. Another example in Figure **??** presents a tutorial to undergo prior to any DfAM evaluation tasks. Users going through DfAM training are expected to evaluate a digital artifact for manufacturability with AM using DfAM tools. As such, the tutorial must instruct on manipulating the digital artifact and interacting with the UI on the DfAM tools. These examples serve to illustrate how tutorials can be designed to prepare users for AM experiences in VR. Other tutorials to prepare users for VR concepts, if required, must be similarly applicable to the main AM experience.

3.2.3. Provide hands-on experience with 3D printing processes

Learning about AM processes involves understanding the functional breakdown of how a process works. This understanding can indicate the effects of each functional component on the manufacturability of a designed artifact. Actively interacting with machines for the different AM processes allows designers to acquire this functional understanding. However, a functional breakdown of the AM process is a prerequisite to designing this active learning experience. As highlighted in Figure **??**, this is because key process-centric concepts must be mapped to instructive tasks to perform in VR. Past work by the authors [148] relies on the work by Williams et al. [162], which offers a decomposition framework focused on five key process-centric concepts:

1. Material identification and storage
2. Supplying material to the system
3. Patterning material or energy
4. Creating primitives
5. Generating support structures.

Completing a task (or set of sub-tasks) associated with an AM process concept can instruct the essential information associated with the concept [164]. Adding declarative information on the instructed concepts, such as textual callouts or audio narration, can aid comprehension. Figure **??** presents an AM process concept being instructed using a task that is designed with this approach.

Figures **??** and **??** illustrate a 60-second-long task performed on a material extrusion and powder bed fusion AM system respectively. Users are verbally instructed about the raw material used for the specific AM process. They are then tasked with loading the material into the machine within a given amount of time. Note the following DfVR considerations from Section 3.2.1 in the design of this task:

- The VR controllers *provide context* to the scale of the raw material and the machine's components.
- Picking up the raw material and feeding it to the machine is done using *direct and*

intuitive actions.

- The *behavior of moving components is mapped* to the constraints expected from the physical system.
- Powder flow (and filament bending) exhibit the *minimum realism required* to naturalize the experience.

By incorporating these considerations, working in VR elicits natural user behaviors identical to those in the physical world. As expected, designers move around the machine and interact with its components to identify what they need to do to complete the task. This means that completing the designed task, both in VR and in person, promotes acquiring procedural knowledge by acting on the declared information. As a result, completing a set of such instructional tasks on the AM process in VR and in person shows identical outcomes [148]. Unlike many in-person experiences, however, VR presents safe, accessible, and controlled digital environments to learn about AM processes [20,21,143]. Further elaborated upon in Section 3.3, it is important to recognize this advantage toward cultivating AM expertise for industrial requirements [150]. This is because building expertise with AM processes is necessary to intuit the fabricated outcome of their design. Task-based instruction of AM process concepts using VR empowers designers to build this competency. Once designers acquire this competency, they can apply it in the DfAM evaluations of their designed artifacts.

3.2.4. Instruct DfAM thinking through artifact evaluations

Virtual reality experiences can replicate the dynamics of working with physical prototypes and tools. Compared to CAx modalities, this yields improved spatial perception and reasoning abilities [108–111]. This is important to recognize because of the high cost of physical prototyping in design processes [130,131]. Specifically, because designs found in the industry can be complex, geometrically or otherwise, often making them infeasible to fabricate. Nonetheless, these designs must be evaluated for manufacturability to promote their incremental improvement. This demand positions VR-driven design evaluations as a cost-effective alternative to physical prototyping.

Improving the quality of an AM artifact requires iterative visual evaluation of its design on DfAM. Doing so can minimize build failures, defects, and frequent rework. For this purpose, an instructional guide to DfAM evaluations is a prerequisite. This guide must consolidate key DfAM heuristics to inform on the manufacturability of an artifact by AM. Past work by the authors [99] consolidated the guidance from the literature on DfAM tools [91,92] into a worksheet for this purpose [165]. Similar to previous tools, the worksheet primarily focuses on functional agnostic DfAM guidance. This is a crucial consideration toward preparing designers to evaluate their designed artifact for 3D printability; i.e., will the 3D printed output come out as designed? As such, knowledge of the artifact's functional requirements is not required for such an evaluation and thus must be avoided to prevent bias or confusion. With this in mind, the designed worksheet instructs designers on the following eight DfAM concepts:

1. Removal of support structures
2. Presence of unsupported overhangs
3. Presence of unsupported bridges
4. Presence of self-supporting features
5. Sharpness/Rounding of cross-sections
6. Size/Area of cross-sections
7. Thinness of features compared to the print resolution
8. Surface finish on non-build direction curved surfaces

Adding visual cues, such as images and text, can support comprehension and declarative knowledge acquisition from each concept. This is demonstrated successfully by existing (non-immersive) tools that serve to promote DfAM thinking during design processes [91,95,97,98]. Figure 3.5 is an example of a user evaluating a digital artifact in VR using a worksheet designed with this approach.

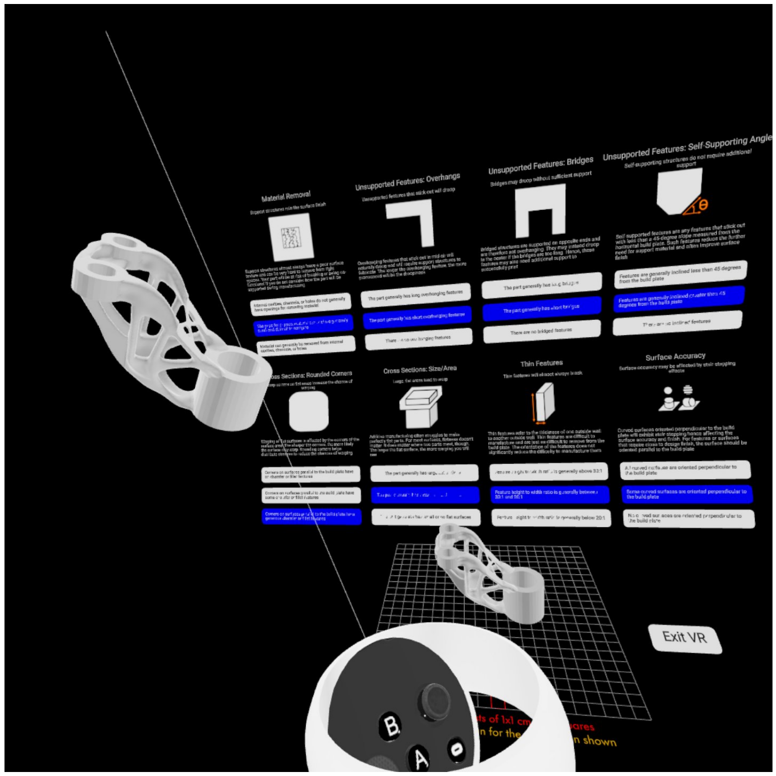


Figure 3.5: Showing a designer evaluation the design of an artifact on DfAM using a pictorial worksheet

As shown in Figure 3.5, the worksheet illustrates and contextualizes different restrictive DfAM heuristics to consider for an AM process. Designers must manipulate the artifact while referencing this information to identify potential design flaws or areas of concern. They must choose options on the worksheet that best describe the design's manufacturability for a given print orientation. Note the following DfVR considerations from Section 3.2.1 in the design of this exercise:

- The VR controllers along with a segregated grid *provide context* to the scale of the artifact.
- Manipulating the 3D model uses *direct actions*, copying physical interactions, while selecting options on the worksheet uses *indirect interactions*, copying digital interactions.
- The user interface of the worksheet is *mapped identically* to digital resources designers

are habituated to using.

By incorporating these considerations, working in VR elicits user behaviors identical to those in the digital and physical worlds. As expected, designers pick up and manipulate 3D artifacts, navigate around the *non-interactables*, and intuitively work with the DfAM worksheet. Like CAx and physical evaluations, this means that evaluating the 3D printability of a design in VR also promotes acquiring declarative knowledge. This knowledge informs designers on whether an artifact is favorably designed for 3D printing. Performing this exercise iteratively per design change can help designers strengthen their DfAM intuition. This trend is observable across modalities of varying immersion when designers evaluate the 3D printability of designs with varying complexity [99]. For early-stage problem-solving with AM, DfAM expertise acquired from such exercises (Figure 3.5) must be harnessed with AM process competency (see Section 3.2.3). As shown in Figure **??**, the intuition that comes with combining these facets of AM knowledge is a prerequisite to problem-solving with AM. This is because the added complexity that comes with the functional context of a design problem, challenges designers to hone their newly acquired intuition. Having the ability to adapt their intuition to simulated 3D printing outcomes will prepare designers for the demands of the AM workforce.

3.2.5. Hone problem-solving skills from simulated outcomes

Cultivating a AM expertise requires designers to actively apply themselves within a problem-driven experience and work within a functional context [115]. Such a functional context is essential in promoting procedural and declarative knowledge acquisition of DfAM and AM process concepts. Creating suitable problem-based experiences requires rethinking traditional DfM methodologies and embracing DfAM principles [100,102,104,163]. Several resources offer perspectives on how to rethink instructional methodologies for problem-solving with AM [2,3,9,10]. However, the key takeaways point to eliciting curiosity in the designers on these key questions:

- *How does adding geometric and functional complexity to the artifact impact its manufacturability?*

Additive manufacturing allows for the creation of complex geometries and assemblies that are difficult to achieve with many subtractive manufacturing methods. Designers may choose to incorporate complexity into their designs, such as lattices or organic topologies, to minimize weight and reduce time to the end product. Before doing so, however, designers must weigh the benefits of adding complexity to its impact on cost, time, and manufacturability.

- *How do different print orientations affect the behavioral properties of the final part?*

  The layer-by-layer nature of the AM technology can yield anisotropic behavioral properties in the fabricated part. The 3D printing orientation, therefore, plays a critical role in the final properties of the part. Designers must evaluate different print orientations and gauge the effects of each orientation on the part's properties.

- *How should the print parameters for the AM process be accounted for during artifact design?*

  Different AM processes influence the fabrication of a design differently. Designers must, therefore, account for printing parameters during the design of their artifacts. These could include 1. the patterning size of material (or energy) and its impact on the print resolution, 2. the minimum angle for inclined features and its impact on the use of support structures and final surface finish, and 3. the density of the infill (hatching) in the part and its impact on printing time and material usage.

- *How does the design of the artifact affect the post-processing requirements for the fabricated output?*

  Many AM processes require different post-processing steps to be implemented on the fabricated output. Operations such as support removal, surface finishing, and heat treatment may be conducted to achieve the desired part properties and appearance. Designers must anticipate post-processing requirements for their artifact and consider its impact on the final product, such as on tolerances, production time, and cost.

Training designers to solve problems with AM must meet two key requirements:

1. Designers must possess strong DfAM insight and process knowledge for an AM process as a prerequisite to intuiting these questions.
2. Designers must apply their AM knowledge in a problem-driven experience and receive simulated feedback on their decisions.

Sections 3.2.3 and 3.2.4 discuss how designers can acquire the necessary DfAM and AM process knowledge in VR to meet the first requirement. Addressing the second requirement, however, requires a VR experience that allows designers to 3D print their designs on a virtual 3D printer. Observing the fabricated output from the AM process and comparing this output to their original design can help designers identify areas of improvement. For this purpose, VR experiences must be developed to simulate the 3D printing process and provide detailed feedback on the fabricated output.

Before discussing the role of the presented feedback in the experience, it is important to consider the fidelity of the 3D printing simulation. This means that the intended use case of the AM experience is important to keep in mind. For this presented work, the use case is to assess and improve the 3D printability of a designed artifact. Therefore, the scope of the 3D printing simulation must focus on displaying a visual representation of the 3D-printed part. As such, the fidelity of the simulation is limited to demonstrating toolpath movement, support generation, layering effects, etc. Not simulated are the physical behavior demonstrated by the fabricated output and the material behaviors in the 3D printing process. This is because simulating such aspects of the AM process is computationally expensive and not essential to this specific use case. This includes not simulating the physics of thermal distortion, material shrinkage, and the impact of process parameters on the part's mechanical properties. Note that the extent of the simulation is dependent on the use case of the AM experience. Therefore, simulating physics at the molecular level may be necessary for other use cases, but at the cost of performance. As exemplified in Section 3.2.3, simulating rigid body physics, such as collisions, assembly joints, and gravity, can naturalize working with an AM system. This demonstrates a use case of conscientiously implementing physics that is *essential* to the AM instruction and not computationally expensive.

Upon deciding on the fidelity of the 3D printing simulation, attention must be given to the feedback provided by the simulation. Figure 3.6 presents an example of a simulated output.

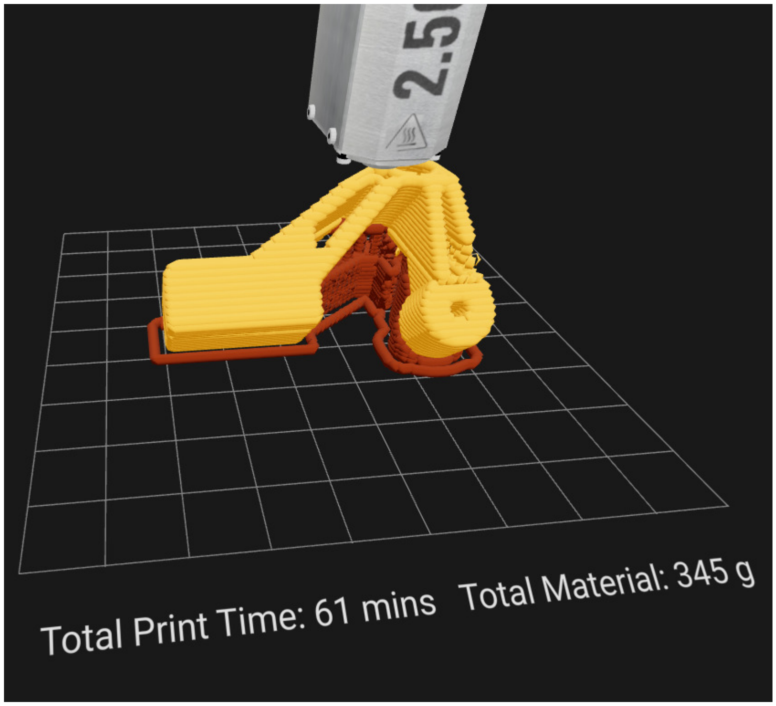


Figure 3.6: Displaying the simulated printing of a designed artifact with information on the print

As displayed in Figure 3.6, the simulated output provides a visual representation of the 3D-printed part. These include the use of support material and the layering effects from the process on the part. Below the 3D-printed part is information on the print, such as the print time and print material. Driven to meet a functional requirement, designers must adopt a new fabrication strategy based on such feedback on time and material usage. Modifying their design or trying a new print orientation are two strategies that can be adopted. Doing so forces them to iteratively acquire new procedural and declarative knowledge, strengthening their cognitive skills in problem-solving with AM. Such an experience emulates traditional problem-solving with physical prototypes, adjusting a designer's mental models [139] and boosting performance [29]. As a result, designers cultivate the expertise they need to make informed decisions on AM, empowering them to solve design challenges in the industry.

3.3. EXAMPLE VR EXPERIENCE FOR AM

The designed VR experiences discussed throughout this work are developed internally by the authors using openly available resources. They leverage WebXR technology and are distributed online on Vercel's[1] hosting service to offer cross-platform access to compatible VR devices. The software utilized to load 3D models and incorporate VR functionality includes the Unity game engine[2] and the Poimandres react libraries[3] powered by three.js[4]. All the VR experiences were tested on the Meta/Oculus Quest 2 and HTC Vive devices only. The remainder of this section showcases an example VR environment designed using the resources listed above for immersive problem-solving with AM.

The authors present a sample VR experience designed to foster AM process knowledge, DfAM intuition, and skills in problem-based artifact generation for AM. The specific features of this experience and their implementation are listed in Table 3.1 and explained later on in this section.

Table 3.1: Listing the technical features designed into the AMVR experience with their proposed utility in design processes

Technical Feature	Use Case
Import and Evaluate Digital Artifacts	Allowing designers to import and manipulate digital artifacts in VR lets them determine the scale, form, and fit of their design. This helps designers evaluate the designs on DfAM to make informed design adjustments before proceeding with the physical fabrication of the artifact
Manipulate AM System Components	Allowing direct manipulation of the components on the AM systems to understand the functionality of the AM processes. This informs designers about the process effects of the specific 3D printing process on their design, fostering their DfAM intuition

[1]Website for Vercel: https://vercel.com
[2]Website for Unity: https://unity.com
[3]Website for react libraries: https://github.com/pmndrs/website
[4]Website for three.js: https://threejs.org/

Technical Feature	Use Case
Slice and 3D Print Designs	Allowing designers to slice and 3D print designs in different orientations lets them compare a variety of potential fabricated outcomes. This helps them analyze the impact of each orientation on the fabrication of their designed features and make changes to their design accordingly
Modify Printing Process	Allow designers to flexibly gather feedback by ignoring physical limitations and altering the speed of the 3D printing process or the visibility of the AM system components. This means designers can visualize typically hidden elements of the AM system. They can also speed up or pause the 3D printing process to assess the print at desired locations

The design of the immersive experience applies the design heuristics described in Section 3.2 to create an environment where designers can:

1. Import, visualize, and evaluate their digital artifacts.
2. Interactively learn about an AM system and its components.
3. 3D print their designs on the system to observe the fabricated output from the AM process.

Figure 3.7 presents an overview of the designed immersive experience created using the considerations listed in Section 3.2.1.

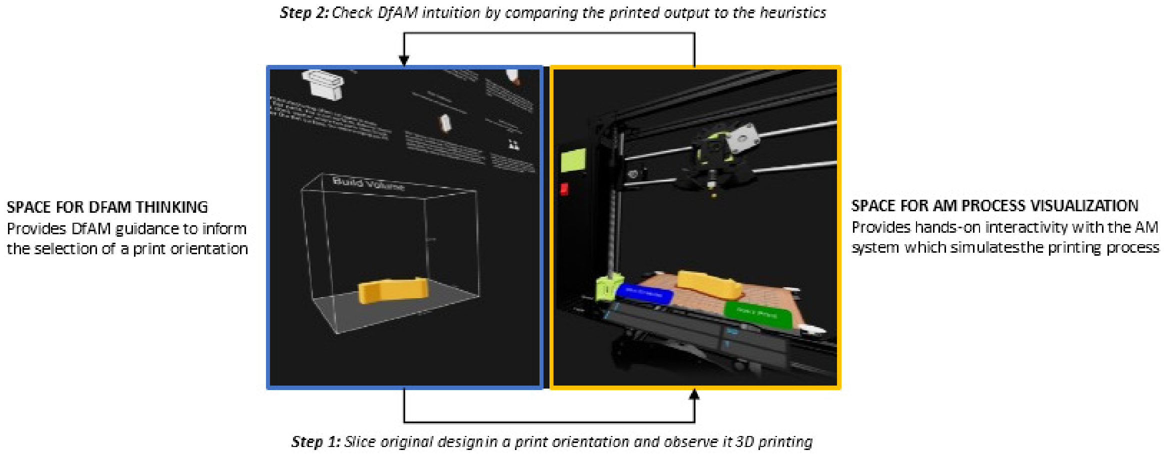


Figure 3.7: Presenting the immersive environment designed by the authors to help develop DfAM and AM process intuition

As shown in Figure 3.7, designers are given a space to import, visualize, and identify a fit or spatial orientation of their design. They are also given a permissible build volume for an AM system to work within. Above this space is information on essential DfAM heuristics, identical to those discussed in Section 3.2.4. Lastly, next to this space is an interactable 3D printer that simulates the 3D printing process being considered. The setup allows designers to slice their design in any orientation and watch it print on the 3D printer as shown in Figure 3.8.

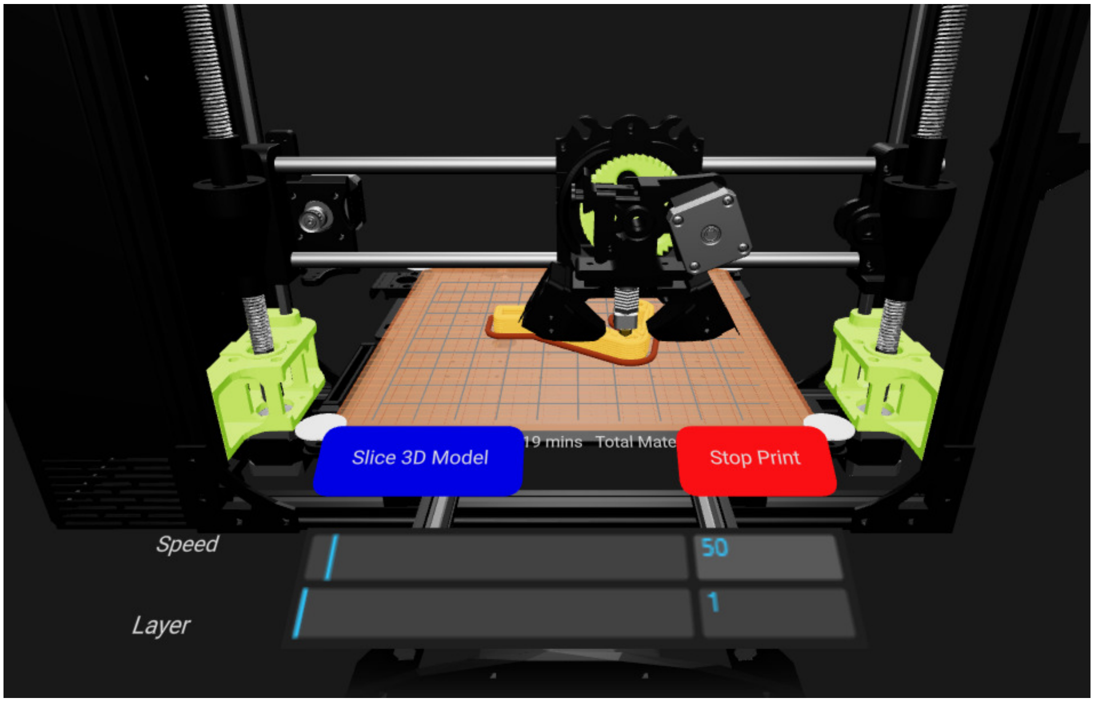


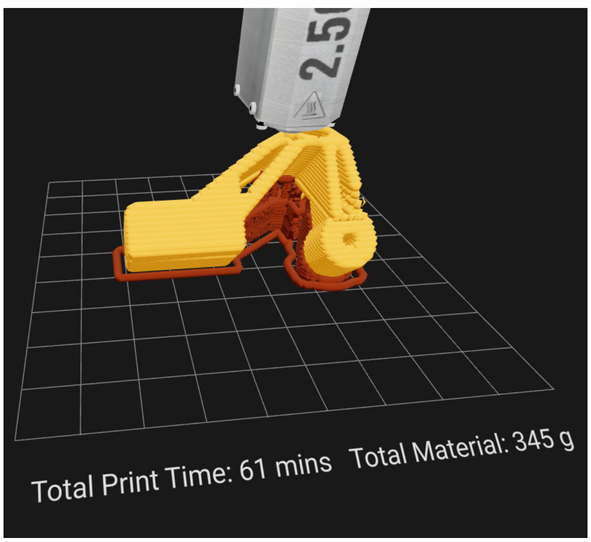
Figure 3.8: Demonstrating the 3D printing a digital artifact on a specific AM process and system

Figure 3.8 also shows the interface used to modify the 3D printing process on the AM system. Designers use the UI to slice and then 3D print artifacts. They can also use the UI to change the simulated speed of the printing process and jump between specific printed layers. Such features on time-dilation for the printing process are not possible in the physical world. Therefore, this digital advantage offers designers flexible visualization of the manufacturability of their design. Designers can also use the UI to tweak the print settings like the infill (or hatching) density and layer height. This further allows them to gauge the effects of such settings on the fabricated output. As explained in Section 3.2.5, the simulation scope is limited to displaying a visual representation of the 3D-printed part. It does not calculate the part's physical behavior, such as part stiffness or tensile strength, nor the mechanical and material behaviors in the 3D printing process, such as material flow or thermal distortion. The visual outcomes of the build parameters during slicing are powered by the Kiri:Moto engine[5]. The 3D model is then rendered using the react-three-fiber library. Other rigid body dynamics, such as

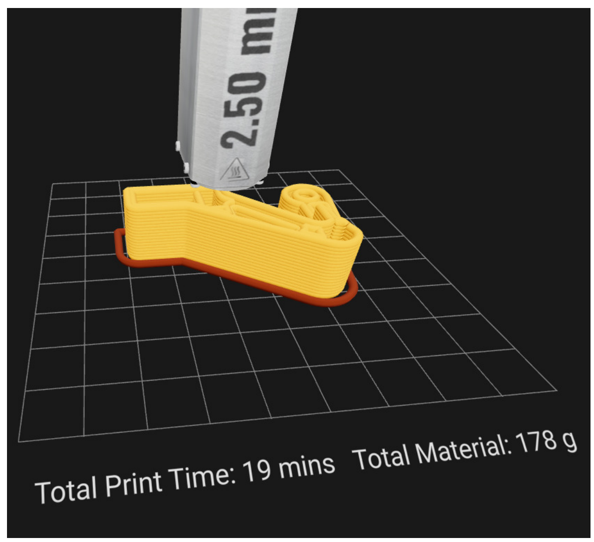
[5]Website for Kiri:Moto slicer: https://docs.grid.space/

those for the 3D printer components, are implemented using the built-in physics engines in Unity and react-three-rapier.

Although designers may iteratively 3D print their designs to check them, they must specifically engage in *informed* trial and error to effectively hone their intuition. This requires resources built into the scene that can inform designers about the DfAM guidelines and heuristics. Designers will need to reference these when evaluating their designed artifact for manufacturability by the AM process. Figure 3.7 shows a DfAM tool identical to the one in Section 3.2.4. This serves to guide the recall of restrictive DfAM heuristics when deciding on how to orient an artifact for 3D printing. Designers need this guidance on DfAM to better assess how orienting the artifact affects the overall quality of the printed artifact. Figure 3.9 demonstrates the importance of instructing the impact of print orientation, using the feedback provided by the simulation.



(a) Print info for orientation 1



(b) Print info for orientation 2

Figure 3.9: Presenting visual feedback on the effects of two different print orientations on the print quality, time, and material used

As shown in Figure 3.9, designers must try orienting their designed artifacts in different orientations. Slicing and 3D printing them highlights the effects of their selected orientation on the fabricated output. This feedback provides designers with a view of the effects of their design decisions. Such feedback is crucial when the complexity of the designed artifact demands a closer inspection of the design. For example, to assess support usage or the quality of intricate features. Therefore as shown in Figure 3.10, designers must compare the printed output to the original design and identify key process effects on their design. This helps the designer understand 3D printing and ask: 1. *can* they additively manufacture the artifact (i.e., consider the limitations of the AM technology)? and 2. *should* they additively manufacture the artifact (i.e., consider the advantages of the AM technology)?

Figure 3.10: Showing a designer comparing the original artifact with the 3D printed output to assess the fabricated quality of their design

As shown in Figure 3.10, the designed user experience must enable a side-by-side comparison of the original digital artifact and the fabricated output. This is a must to help answer, *can-they* and *should-they*, 3D print their designs. However, these can not be addressed without acquiring DfAM expertise for the range AM processes. This is because the manufacturability of a design is dependent on the AM process being considered. Figure **??** demonstrates how manufacturing a design is different with two different AM processes, illustrating the need for the breadth of AM process knowledge.

As shown in Figure **??**, designers are introduced to manufacturing with high-barrier-to-entry AM systems like powder bed fusion inside a safe and accessible environment. This is because digital experiences can ignore physical limitations [56–58,145] to provide visual access to otherwise inaccessible observations and incomprehensible phenomenons. The designed experience also allows designers to selectively alter the visibility of the components on the AM system. This allows them to observe the 3D printing process in a way that is otherwise highly dangerous or simply not possible with the physical systems. Designing immersive experiences with such capabilities is, therefore, a key step toward accessibly fostering in-depth AM expertise for industrial requirements.

3.4. CONCLUSION AND FUTURE WORK

The goal of this research is to train design students to solve globally emerging design problems with AM. To advance this goal, this work proposes a framework to create immersive VR experiences that foster DfAM and AM process intuition. Insights gained from topics in education and learning, AM, and VR informed the design of the framework, within modern VR capabilities. It can be used to develop training programs and curricula, empowering designers with the skills to design and evaluate digital artifacts for AM. By cultivating such AM talent, organizations can reduce the time and cost of producing end-use products that are powered by AM. With this motivation, this work demonstrates the application of the proposed framework with an example VR experience for problem-solving with AM. This is a first step towards developing immersive VR experiences for DfAM and AM process training. As a result, ongoing studies are exploring the effectiveness of the designed experience in helping design students apply DfAM in analytical problem-solving. The authors plan to expand on this work and create AM-focused training programs and curricula to institutionally prepare design students with AM expertise. However, before the proposed framework can be applied to such programs, it must be refined to improve the effectiveness of future designed experiences.

The presented example uses the established DfVR guidance in Section 3.2.1 with the proposed framework. However, several technical considerations must be addressed to improve the example experience. First, minimizing experiential cognitive load and time to master navigating the VR environment is paramount to efficient training. Designers must go through an optimized tutorial to learn the basics of VR experiences within the AM context. For this purpose, future research should investigate human-VR interactions and extract key learnings to inform the design of the tutorial. Additionally, the presented platform for AM education does not reflect the full scope of education and learning or the effect of cognitive load on immersive experiences. Future studies should investigate incorporating rigorously designed curricula and training programs into the immersive environment. The presented framework was also developed by observing outcomes from designers with similar levels of prior knowledge. Specifically, the participants primarily had some informal or formal knowledge of DfAM and AM processes. Future work must study the impact of this framework on designers with other levels of prior experience. Furthermore, the technical design is limited by current VR technology capabilities, such as headset resolution, which affects the final fidelity of the 3D printing simulation. Specifically, this work demonstrated 3D printing at a 2.5 mm XY and 1.75 mm Z resolution. This was constrained by our VR technology which could not render resolutions smaller than 1 mm. Therefore, future work should identify techniques to enhance the fidelity of designed experiences. This will promote incorporating a wider range of AM process resolutions and capabilities for DfAM evaluation and AM problem-solving. Lastly, the proposed framework allows designers to import their designs and 3D print them. However, this work did not account for the range of complex artifacts that designers create. It also did not study the impact of the complexity of the designs on the effectiveness of the framework. Future work must conduct a deeper dive into how the framework impacts working with designs of varying complexity.

Chapter 4

IMMERSION IN AM PROCESS EDUCATION

4.1. INTRODUCTION

The additive manufacturing (AM) industry expanded by nearly 7.5% to roughly $12.8 billion within the year 2020 [166] with a 2x growth forecasted to roughly $37.2 billion for 2026 [167]. This continued market growth is driven by the demand for rapid design and manufacturing of complex products by leveraging AM capabilities in geometrical, hierarchical, functional, and material complexity. This can be observed in expert projections that suggest that by 2030, manufacturing of less critical spare parts will be primarily driven by AM and a significant amount of AM products will leverage capabilities in multi-material fabrication and product development with embedded electronics [9]. Although the demand for AM continues to grow, there is a deficit of designers and engineers in the workforce suited to meet this demand and apply the technology to different product design opportunities [140,141]. Inadequate in-house AM and design for additive manufacturing (DfAM) knowledge due to this deficit of designers presents a barrier to the integration of AM [12,13] within organizations. Therefore, the future workforce must be equipped with the skills and knowledge in AM and DfAM to meet this growing demand for AM and drive future innovation in industrial product development.

Design and process-centric AM education can help prepare the AM workforce [11] and empower designers to innovate with AM. The process-dependent nature of DfAM and applying AM in product development [6–8] indicates that in-depth process-centric education for the full range of AM processes can complement the growth of DfAM intuition and improve a designer's versatility with AM. However, observable barriers to entry faced by AM systems (e.g., cost, safety, required infrastructure [20,21,143]) inhibit designers from accessing knowledge for AM processes like powder bed fusion (PBF) within educational institutions and communities. There is a need to provide accessible and in-depth education on the range of AM systems and there is an opportunity to do so by leveraging virtual mediums such as computer-aided instruction (CAI) and virtual reality (VR). This research is thus motivated to explore this opportunity and address this inaccessibility to AM knowledge to improve the design capabilities of the future AM-driven design and engineering workforce.

Simulation and gaming-structured CAI has historically addressed this need and enhanced different learning outcomes [146,147], including declarative and procedural knowledge, in science, engineering, and manufacturing [61,62,145,168] that typically require in-person instruction. While non-immersive virtual tools like CAI can potentially benefit AM education, research shows that enhancing immersion and presence can improve the experience and its outcomes [106,107,110,111,149]. This is because the characteristics of the media, tools, and human-related factors, such as spatial perception and reasoning, and psychomotor skills, strongly influence the design, learning, or engineering experience [32]. There is, therefore, an opportunity to explore immersive VR in addition to CAI as a tool for AM education.

Past work indicates that VR improves the development of declarative and procedural knowledge [25], cognitive and affective skills [26], and memory recall [71] when compared to CAI. Immersive technology is already driving industry uses of VR in engineering and manufacturing to support decision-making and enable innovation [64] by enhancing engineering education [149], allowing engineers to make fewer mistakes in procedural manufacturing and assembly tasks [106] when compared to in-person product assembly and take lesser task completion times when compared to both CAI and in-person [106,107] conditions. Literature even shows early promise in developing designer intuition in design and process-centric AM concepts [138,169] using VR. There are mixed effects of VR technology in science and education [27,72–75] that highlight how the environmental and pedagogical conditions of learning strongly affect the learning experience. However, inductive learning techniques such as task-based and problem-based learning in engineering [44,49] are well suited for AM education [103] and present pedagogical frameworks that lean toward procedural and declarative learning experiences that are ideal within immersive learning. Past work also suggests that immersion and presence have mixed influences in the observed cognitive load as influenced by the manual operations required during the experience [83–88]. Different cognitive load aspects affect learning [33] including variations in modality between learning mediums of varying immersion [31]. Therefore, it is crucial to gauge how immersive experiences specifically for AM education can affect cognitive load to better understand the simultaneous effects on learning. Collectively, these observations from the literature strengthen the need to compare mediums of varying immersion and presence on the specific application of AM education to expand the existing knowledge bases in both AM and VR.

4.2. RESEARCH QUESTIONS

Immersion and presence in virtual environments give users a “vivid illusion of reality” [25,154] where the reality of the physical world exhibits the highest levels of immersion and presence. Virtual realities are a collaboration of immersion and presence [26,154] surrounding users in a digital space that mimics the sensory elements of the physical reality and are thus measured as the extent to which the virtual environment can surround users to simulate immersion and presence. Traditional computer displays typically fall under non-immersive VR and head-mounted displays (HMDs) fall under immersive VR [26]. Although past work indicates that there may be differences in educational effect specifically due to immersion or presence or both [27,73], this research does not differentiate the three mediums specifically between immersion and presence and assumes an overall change in both from CAI to VR to REAL. For further sake of clarity, this research simplifies the objective and subjective relationship between immersion and presence and henceforth refers to both solely using the term immersion with the following distinctions between the studied mediums: CAI = non-immersive virtual medium (i.e., a flat computer screen), VR = immersive virtual medium (i.e., an HMD with controllers), REAL = immersive physical medium (i.e., the physical world).

Literature shows that the immersion of a medium strongly influences the learning and the mental effort experienced during an educational experience; however, limited work in the supportive knowledge for AM and DfAM [138] investigates how the medium in which a designer learns about AM affects their education. New knowledge on how the mediums affect the AM educational experience can be leveraged to further improve industrial product development processes by better training and equipping designers for the AM-driven product demands in the workforce. This research, therefore, aims to address this gap in the literature by exploring the following key research questions:

Research Question 1. *How do the differences in immersion between CAI, VR, and REAL mediums affect knowledge gain when learning about ME and PBF?*

We hypothesize that the PBF group will generally show higher knowledge gains than the ME group [168]. For both AM processes, learning through VR and REAL will yield higher knowledge gains than will learning through CAI with identical trends observed between the two immersive conditions [138]. This is expected due to the effects of the varying capabilities offered by the conditions during the procedural learning experience: capabilities such as interactivity, immersion, psychomotor coordination, memory recall [71], and spatial perception and reasoning [32].

Research Question 2. *How do the differences in immersion between CAI, VR, and REAL mediums affect cognitive load when learning about ME and PBF?*

We hypothesize that the PBF group will generally show similar cognitive load trends to the ME group [168]. For both AM processes, learning through VR and REAL will yield lower cognitive load trends than will learning through CAI with identical trends observed between the two immersive mediums [83,87]. This is also expected due to the effects of the varying capabilities offered by the conditions which affect the difficulty of navigating the learning environment and conducting self-learning actions within the environmental restrictions. Specifically, due to the changes in difficulty of processing task-related information and performing manual operations [83,84,87,88] with the change in immersion.

4.3. MATERIALS AND METHODS

Participants in this research were first-year undergraduate students recruited from an introduction to engineering design course at an R1 university. Volunteers were first informed of their rights and options as per IRB protocol before conducting the study. This information included reassurances that their participation would be anonymous but they may choose to opt-out of participating or releasing their data in this research if they experience physical, mental, or ethical discomfort of any kind and that their participation (or lack of) would not affect their academic standing. Participants in the VR condition were reminded to use these rights should they experience nausea, dizziness, or sickness when using the VR equipment. Those who opted in to participate were provided an online Qualtrics survey that they completed on their PCs. Participants volunteered as groups during class time or independently outside of class time and were assigned to one of the three conditions (i.e., either CAI, VR, or REAL) for one of the two AM processes (i.e., either ME or PBF) by a study coordinator. Balancing the number of data points between all the conditions was also handled by the study coordinator. During the study, participants shared information about their background and interests in AM (see Section 4.3.1) and a pre-post assessment of their AM process knowledge and cognitive load (see Section 4.3.3) from our 13-minute intervention (see Section 4.3.2). This section elaborates on the specifics of the designed experimentation.

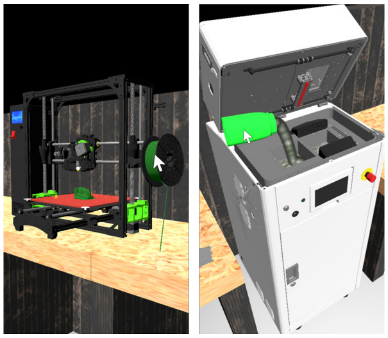
4.3.1. Assessing the participants' backgrounds

Participants first shared their interest and motivation regarding learning about AM and using AM. They indicated their agreement to the posed questions on interest and motivation on a 5-point likert scale that ranged from strongly agree to strongly disagree [170]. They also shared their awareness of the overall AM technology. Collectively, the data on interest, motivation, and AM awareness helped strengthen the statistical analysis of the results of knowledge gain and cognitive load by authenticating the participant's engagement in the study and accounting for prior knowledge that could affect the findings. Participants in the CAI and VR conditions also shared their comfort levels in working with or interacting with 3D models (i.e., virtual objects) within their specific conditions. Awareness of interaction in CAI and VR was also recorded on a 5-point likert scale that covered identical options in each topic [170]. Before moving on to the experiment, participants completed the pre-quiz [171] for their assigned AM process, data from which was used with the post-quiz data to assess knowledge gain.

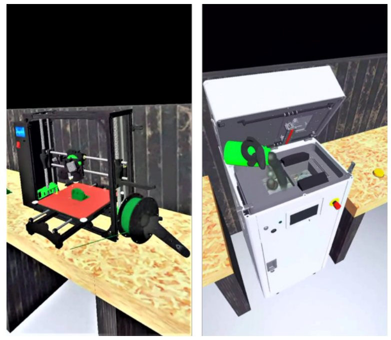
4.3.2. Completing the tutorial and intervention

The designed experiment included a custom 4-minute tutorial for the assigned condition that instructed them on how to navigate and interact within their condition. Participants in the CAI, VR, and REAL conditions practiced performing tasks and completing objectives identical to the upcoming intervention to familiarize themselves with the capabilities and limitations of their medium. The tutorial, therefore, instructed participants on tasks that required familiarity in picking up and moving objects and navigating within a bounded space.

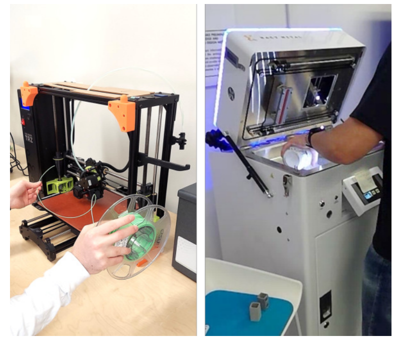
Completing the tutorial session was followed by the 13-minute intervention for the assigned AM process where they learned about the AM process and completed tasks to reinforce their learning. Participants assigned to the CAI condition were directed to the tutorial and intervention in the survey on their computers. Those assigned to the VR and REAL conditions were directed to designated study zones where they were provided the equipment and tools needed to complete the exercise. Participants in the VR condition were given a wired HTC Vive headset and a pair of wireless controllers. Participants in the REAL condition were directed to the physical objects and machines and were instructed to follow along with the audio playing on a device next to the machine. All conditions were designed to foster the same level of involvement during testing while allowing free interaction with the machines, objects, and environment to the extent permitted within the given medium. The virtual environments for the CAI (see Figure 4.1a) and VR (see Figure 4.1b) conditions were designed as web applications using Unity: a cross-platform game engine popularly used to design virtual experiences, and included virtual parts and machines to interact with. The design of the REAL condition (see Figure 4.1c) included physical parts and machines where the physical parts were manufactured using the specific AM process the participants learned about and underwent no post-processing to specifically highlight the effects of the manufacturing process.



(a) CAI interaction using a computer mouse and keyboard for task completion



(b) VR interaction using a VR controller and physical movement for task completion



(c) REAL interaction using physical movement for task completion

Figure 4.1: Showcasing a participant completing a 60-second task of loading material into the AM machine to highlight the experimental design setup across the conditions and between the AM processes

Educational concepts from a functional decomposition framework (Figure 4.2) were used as the pedagogical foundation for the intervention to provide an on-par comparison between the AM processes when observing knowledge gain and cognitive load.

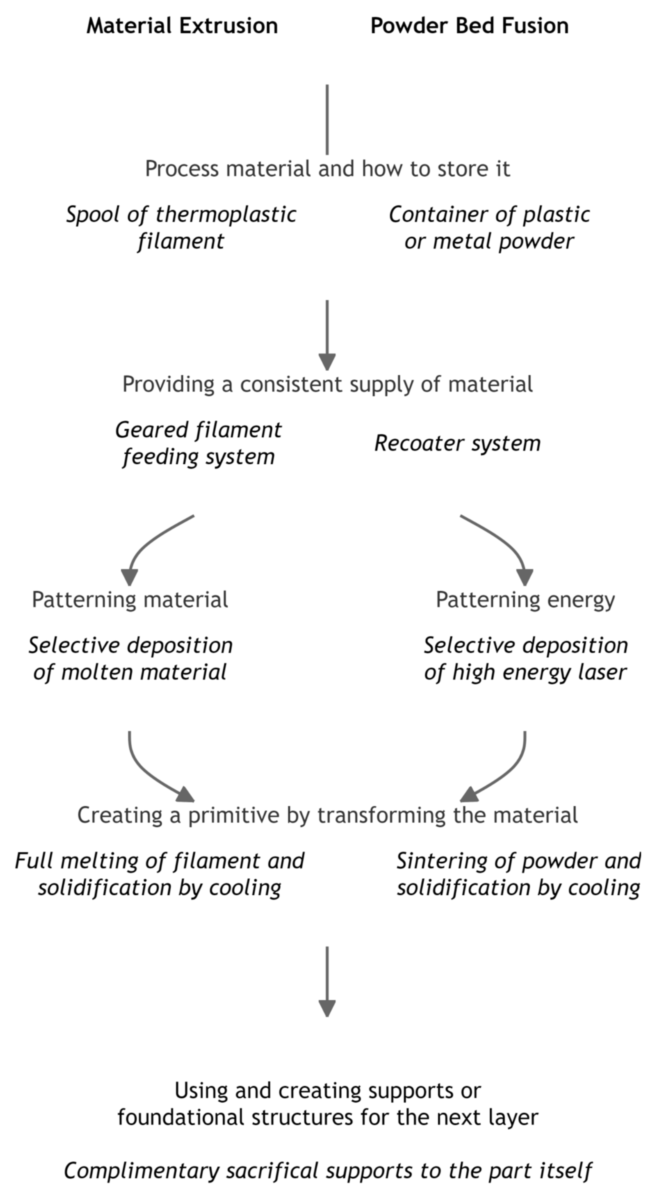


Figure 4.2: Highlighting the concepts derived from the functional classification framework that are used to design the educational experiences and define the relevant tasks

Based on the functional classification framework by Williams et al. [162], this decomposition framework focused on five key process-centric concepts: i) material identification and storage, ii) supplying material to the system, iii) patterning material or energy, iv) creating primitives, and v) generating support structures. Figure 4.1 illustrates a 60-second-long sample task performed during the intervention for the different conditions and AM processes where participants were verbally instructed about the raw material used for the AM process and were then encouraged to load the material into the machine given sufficient time to attempt the task on their own. All tasks were similarly associated with each concept [164] scripted specifically to the Lulzbot Taz 6 for the ME condition and the Xact Metal XM200C for the PBF condition. To focus on how variations between the conditions influenced the difficulty in performing tasks during the intervention, tasks between the ME and PBF conditions were designed to be of identical conceptual difficulty as per the decomposition framework derived from past work by Williams et al. [162]. All tasks were constrained to those that would be safe and permitted in a typical in-person learning environment with physical machines. To ensure the safety of the participants in the REAL condition, the physical machine for the ME group was not powered and the physical machine for the PBF group only housed the skeletal structure of the machine with functionality suitable for safe demo purposes. Additionally, the PBF group handled a powder-like substitute to teach participants about the raw material for the PBF process.

4.3.3. Measuring knowledge gain and cognitive load

Paired data from a pre-and post-quiz assessment was used to measure knowledge gain as the difference in quiz scores. One quiz variant for each AM process was designed and participants completed the quiz specific to their assigned process [171] before and after the intervention. The questions in the quiz were formulated using the same terminology as used in the intervention. All the questions were objective, single-answer, or multiple-answer type questions to ensure simplicity in calculating the quiz scores and knowledge gained through the change in quiz scores. Every question offered an “I don’t know” option to minimize the probability that students would try to guess the correct answer. No negative scoring was done and all questions were worth a maximum of 1 point. Certain concepts required adding additional questions to the quiz to ensure that all the relevant elements of the concepts were tested, therefore, the number of questions differed between the two conditions (i.e., ME had 10 and PBF had 9). Pre and post-quizzes were tallied and normalized where normalization entailed 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 scores. Participants reported their cognitive load using the Workload Profile Assessment (WPA) tool [172] by sharing the mental effort they exerted during the learning experience. Participants scored each of the eight workload profile dimensions (i.e., the perceptual, response, spatial, verbal, visual, auditory, manual, and speech) independently between 0 and 10 to represent their exerted mental effort. They received a textual and audio description of each dimension to review, along with an example of how cognitive resources for each dimension might be applied to a relatable task to better assess their cognitive load.

4.4. RESULTS

This research collected a sample size of data points with the distribution shown in Table 4.1.

Table 4.1: Showing the distribution of participants across the conditions and AM processes

	CAI	VR	REAL
ME	79	18	13
PBF	82	21	24

From this participant pool, we collected demographic data, knowledge gain data, and cognitive load data and report this collective data and the results from its analyses while maintaining all outliers. To account for the complexity of the repeated measures experimental setup and the presence of multiple dependent and independent variables in its statistical analysis, this research uses linear regression modeling (lm) for the demographic and cognitive load data and linear mixed-effects regression modeling (lmer) for the knowledge gain (i.e., pre-post quiz) data. A 95% confidence interval was generally used to determine statistical significance (i.e., $p < 0.05$), however, certain trends around the 95% interval are discussed as emerging trends and not statistically significant under the discretion of this research. The assumptions for linear regression and linear mixed-effects regression modeling were checked for violations using the Peña and Slate [173] and the Loy and Hofmann [174] procedures respectively. This research did not find any observable violations and relies on the acceptable range for the robustness of *lms* and *lmers* in its reported findings.

4.4.1. Demographic analysis of the participants

Regressing the interest and motivation levels on the centered process (ME=-0.5, PBF= 0.5; between-subjects variable) showed no observable statistically significant difference between participants assigned to both the AM processes in interest and motivation. However, regressing the interest and motivation levels on the centered condition (CAI= -0.5, VR= 0, REAL= 0.5; between-subjects variable) showed a significant effect within conditions in interest and motivation such that participants generally reported higher interest and motivation in AM as the condition changed from CAI to VR to REAL (for interest to learn AM: $b = 0.306$, $F(1, 233) = 8.085$ [$t(233) = 2.843$], $p = 0.005$, for interest to use AM: b= $b = 0.287$, $F(1, 233) = 5.395$ [$t(233) = 2.323$], $p = 0.021$, for motivation to learn AM: $b = 0.414$, $F(1, 233) = 9.086$ [$t(233) = 3.014$], $p = 0.003$, for motivation to use AM: $b = 0.404$, $F(1, 233) = 8.515$ [$t(233) = 2.918$], $p = 0.004$). As shown in Figure 4.3, many participants agreed or strongly agreed that they were interested and motivated to learn about and use AM within each of condition and each AM process.

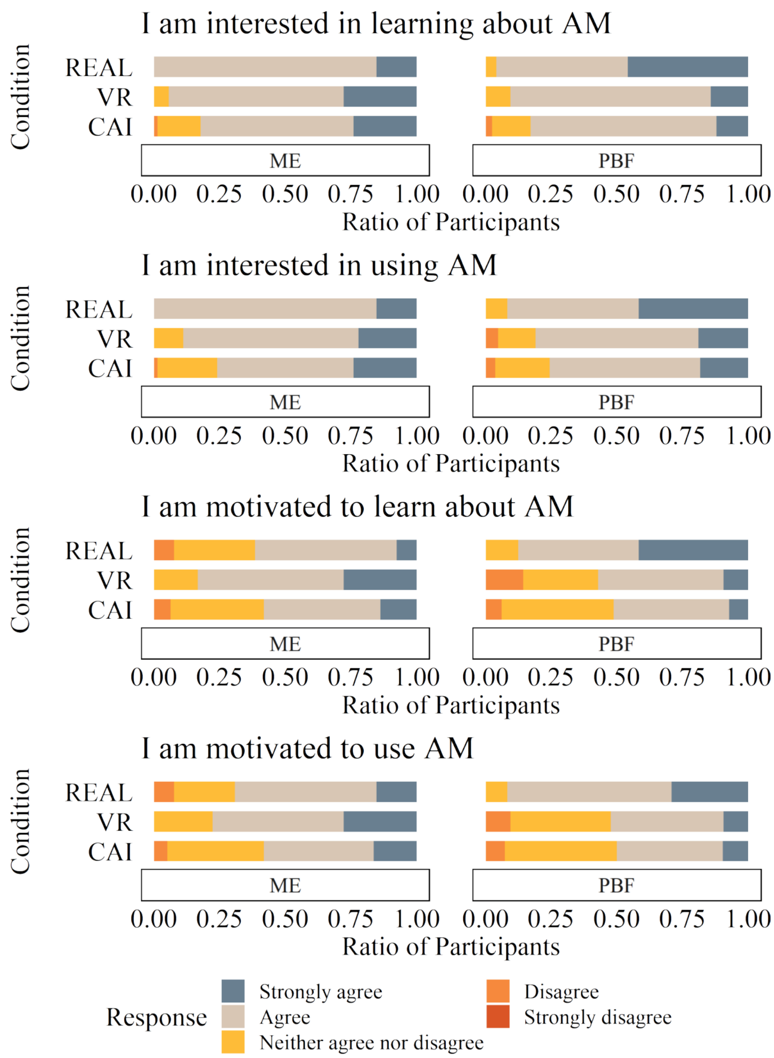
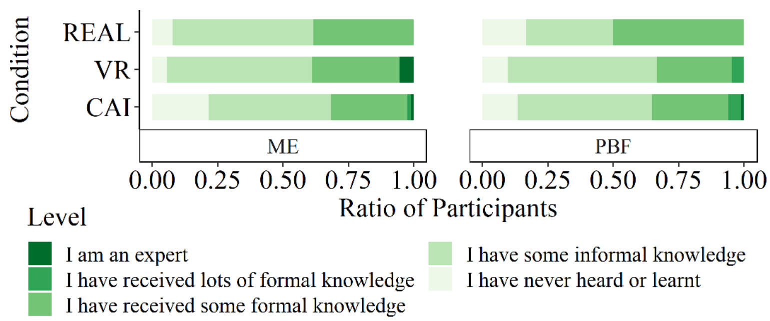


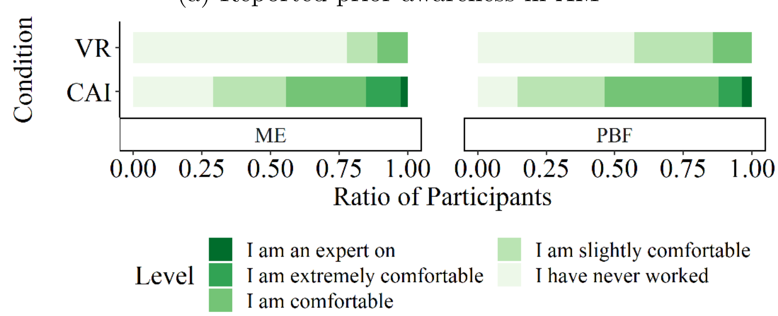
Figure 4.3: Showcasing the reported interest and motivation to learn and use AM across the conditions and AM processes

These levels of interest and motivation indicate that participants were authentically engaged with the study and thus strengthen the authenticity of the data collected for knowledge gain and cognitive load.

Regressing the distributions of the prior awareness in AM on the centered condition (CAI= -0.5, VR= 0, REAL= 0.5; between-subjects variable) and process (ME=-0.5, PBF= 0.5; between-subjects variable) showed no observable statistically significant difference between the conditions, $b = 0.147$, $F(1, 233) = 1.087$ [$t(233) = 1.043$], $p = 0.298$, or between the AM processes, b = 0.02, F(1, 233) = 0.024 [t(233) = 0.156], p = 0.876. As shown in Figure 4.4a, this means that participants' perceived awareness with general AM across the conditions and AM processes was generally identical and therefore was not accounted for as a variable of interest in later analyses.



(a) Reported prior awareness in AM



(b) Reported prior comfort with CAI and VR

Figure 4.4: Showcasing the prior awareness in AM and comfort levels with VR and CAI across the conditions and AM processes

Regressing the distributions of the prior comfort with interaction in CAI and VR on the centered condition (CAI= -0.5, VR= 0.5; between-subjects variable) and process (ME=-0.5, PBF= 0.5; between-subjects variable) showed a significant difference between the conditions, b = -0.987, F(1, 233) = 31.223 [t(233) = -5.588], p $<$ 0.001, but not between the AM processes, b = 0.229, F(1, 233) = 1.681 [t(233) = 1.296], p = 0.196. This means that participants in the CAI condition generally had a significantly higher comfort with CAI technology than did participants in the VR condition with VR technology. This can be observed in Figure 4.4b where a significantly higher number of participants reported that they had never worked with VR before the study indicating that they were novices to VR. These results were expected as this research worked with primarily first-year undergraduate students from an engineering design course at an R1 university who would have completed some CAI course requirements, and likely not have completed any VR course work. While, the varying comfort levels between CAI and VR could influence the study, with the limited scope in mind for this work, we acknowledge the limitation of not accounting for technology comfort levels which will be considered as an opportunity for future work.

4.4.2. Effects on knowledge gain by immersion for the different AM processes

Figure 4.5 shows the key results of the analysis of knowledge gain for each AM process across each condition.

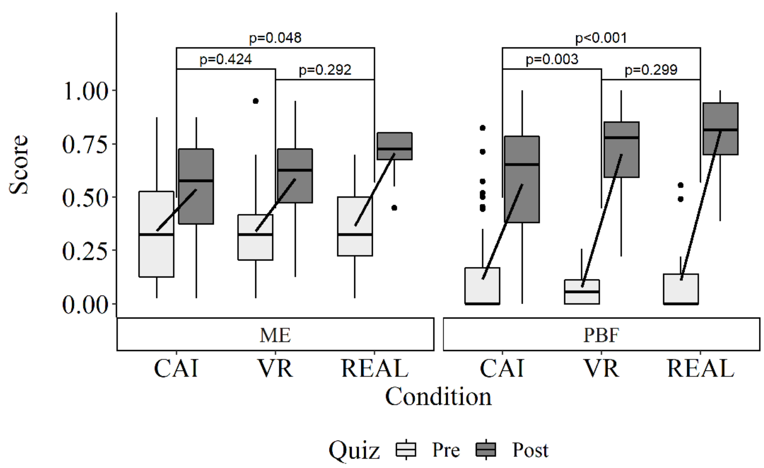


Figure 4.5: Showcasing the distribution of quiz scores and the net knowledge gain as affected by the three conditions between the two AM processes

For this analysis, quiz score (collapsed pre and post-quiz scores) was regressed on the centered variables for condition (CAI = -0.5, VR = 0, REAL = 0.5; between-subjects variable), and process (ME = -0.5, PBF = 0.5; between-subjects variable), quiz time (pre-quiz = -0.5; post-quiz = 0.5; within-subjects variable), and the interaction of these three variables (condition*process*quiz) as the covariates. This analysis also included a by-subject random intercept and a by-subject random slope for the quiz variable, utilized restricted maximum likelihood estimation to iteratively modify the parameter estimates to minimize the log-likelihood function, and evaluated this model with the Kenward and Rogers (KR) adjustment [175]. The following results reported from the analysis focus on each detailed effect when controlling for all other main effects and interactions in the model.

4.4.2.1. Process-wise comparison of knowledge gain across the conditions

To understand the differences in the knowledge gain between the conditions and AM processes, we estimated the two-way interaction between condition and quiz time, $b = 0.2$, $F(1, 233) = 21.65$ [$t(233) = 4.653$], $p < 0.001$, and process and quiz time, $b = 0.323$, $F(1, 233) = 67.504$ [$t(233) = 8.216$], $p < 0.001$. These results show that the knowledge gain significantly differed between the conditions and the AM processes. Specifically, participants in PBF generally experienced a higher knowledge gain than participants in ME. Participants also generally experienced a higher knowledge gain as the condition changed from CAI to VR to REAL.

Conducting pairwise-comparison analyses for process within each condition provided specific insight into the differences in knowledge gain between the AM processes for each condition. Results showed that knowledge gain significantly differed when comparing ME to PBF in the CAI ($b = 0.25$, $F(2, 231) = 43.56$ [$t(231) = 6.6$], $p < 0.001$), VR ($b = 0.38$, $F(2, 231) = 24.01$ [$t(231) = 4.9$], $p < 0.001$), and REAL ($b = 0.36$, $F(2, 231) = 18.49$ [$t(231) = 4.3$], $p < 0.001$) conditions. This means that the participants experienced a higher knowledge gain for PBF than for ME in each condition.

Conducting additional pairwise-comparison analyses for condition within each process provided further insight into the differences in knowledge gain between the conditions for each process. As shown in Figure 4.5 for the ME process, knowledge gain did not significantly differ in comparisons between CAI to VR ($b = 0.051$, $F(2, 231) = 0.64$ [$t(231) = 0.8$], $p = 0.424$) and VR to REAL ($b = 0.093$, $F(2, 231) = 1.21$ [$t(231) = 1.1$], $p = 0.292$), but showed an emerging trend between CAI to REAL ($b = 0.144$, $F(2, 231) = 4$ [$t(231) = 2$], $p = 0.048$). However as shown in Figure 4.5 for the PBF process, knowledge gain significantly differed in comparisons between the CAI to VR ($b = 0.178$, $F(2, 231) = 9$ [$t(231) = 3$], $p = 0.003$) and CAI to REAL (b = 0.253, $F(2, 231) = 20.25$ [$t(231) = 4.5$], $p < 0.001$), but not in the comparison between VR to REAL (b = 0.075, $F(2, 231) = 1$ [$t(231) = 1$], $p = 0.299$). This means that the participants did not experience a statistically significant difference in knowledge gain in ME between CAI, VR, and REAL, however, they did experience a higher knowledge gain in PBF as the condition changed from CAI to VR or REAL.

4.4.2.2. Analyses supporting the observed knowledge gain results

The main analysis showed a significant effect of the quiz time on quiz scores such that on collapsing the condition and process categories, participants generally scored higher in the post-quiz than in the pre-quiz, b = 0.424, $F(1, 233) = 464.312$ [$t(233) = 21.548$], $p < 0.001$. As can be observed in Figure 4.5, this means that participants generally experienced a statistically significant knowledge gain (i.e., the difference between pre-quiz and post-quiz scores) because the post quiz scores are generally higher than the pre-quiz scores across the conditions and AM processes.

To evaluate whether scores specifically improved significantly for participants in each condition and for each process, we examined the simple effects of the quiz time for each condition and AM process by re-centering condition and process around each level in the variable and then performing the analysis using those variables in turn. Condition was re-centered around CAI (CAI = 0, VR = 0.5, REAL = 1), VR (CAI = -0.5, VR = 0, REAL = 0.5), and REAL (CAI = -1, VR = -0.5, REAL = 0) respectively, and process was re-centered around PBF (PBF = 0, ME = 1) and ME (PBF = -1, ME = 0) respectively. These analyses provided insight into whether there was a significant knowledge gain for participants in each condition or only for one of the conditions and in each process or only for one of the processes. The simple effects of quiz time (see Table 4.2) showed that participants in each condition and process scored significantly higher on the post-quiz than on the pre-quiz. These results can also be observed in Figure 4.5 which shows that the post-quiz scores are much higher than the pre-quiz scores for all the conditions and processes, therefore suggesting that the knowledge gain was significant across the board.

Table 4.2: Highlighting the simple effects from the pre- to post-quiz comparisons across the conditions and AM processes

Process	Condition	Estimate	F.value	t.ratio	p.value
PBF	REAL	0.7	198.81	14.1	< 0.001
PBF	VR	0.62	139.24	11.8	< 0.001
PBF	CAI	0.44	278.89	16.7	< 0.001
ME	REAL	0.34	25	5	< 0.001
ME	VR	0.24	18.49	4.3	< 0.001
ME	CAI	0.19	51.84	7.2	< 0.001

To better understand how the trends in quiz scores contributed to the significance of the observed knowledge gain, we also evaluated the simple effects of process and condition at each quiz time (pre-quiz and post-quiz). We did so by re-centering quiz time around pre-quiz (pre-quiz = 0, post-quiz = 1) and post-quiz (pre-quiz= -1, post-quiz = 0), respectively, and then performing the analysis with those variables in turn. This allowed us to understand whether the participants differed from one another in pre-quiz, post-quiz, or both, between the conditions and processes. The simple effects analysis of condition and process at each quiz time (Table 4.3) show that pre-quiz scores for each process were not significantly different between the conditions (Table 4.3a); however, pre-quiz scores for ME were significantly higher than pre-quiz scores for PBF in each condition (Table 4.3b). This means that participants in the ME group generally had more prior knowledge of ME than participants in the PBF group had of PBF.

Table 4.3 and Figure 4.5 also show that the post-quiz scores did not significantly differ between the AM processes for each condition (Table 4.3b) suggesting that participants in both AM processes generally ended up with equivalent knowledge within each condition. However, Table 4.3a shows that post-quiz scores were significantly impacted by the conditions within each AM process. For the ME process, Table 4.3a and Figure 4.5 show that the post-quiz scores did not significantly differ between CAI to VR and VR to REAL, but they did significantly differ

Table 4.3: Highlighting the simple effects from the comparisons between conditions and AM processes at different quiz-times

(a) Quiz scores compared between CAI, VR, and REAL for each AM process

Process	Comparison	Quiz	Estimate	F.value	t.ratio	p.value
ME	CAI to VR	Post	0.04	0.49	0.7	0.437
ME	CAI to VR	Pre	0	0	0	0.982
ME	CAI to REAL	Post	0.16	4.84	2.2	0.022
ME	CAI to REAL	Pre	0.02	0.09	0.3	0.695
ME	VR to REAL	Post	0.11	1.69	1.3	0.184
ME	VR to REAL	Pre	0.02	0.09	0.3	0.735
PBF	CAI to VR	Post	0.14	5.29	2.3	0.018
PBF	CAI to VR	Pre	-0.03	0.49	-0.7	0.47
PBF	CAI to REAL	Post	0.24	19.36	4.4	< 0.001
PBF	CAI to REAL	Pre	0	0	0	0.935
PBF	VR to REAL	Post	0.1	1.96	1.4	0.141
PBF	VR to REAL	Pre	0.03	0.25	0.5	0.597

(b) Quiz scores compared between ME and PBF for each condition

Condition	Quiz	Estimate	F.value	t.ratio	p.value
CAI	Pre	-0.22	49	-7	< 0.001
VR	Pre	-0.26	15.21	-3.9	< 0.001
REAL	Pre	-0.25	12.96	-3.6	< 0.001
CAI	Post	0.02	0.36	0.6	0.532
VR	Post	0.11	1.96	1.4	0.139
REAL	Post	0.1	1.44	1.2	0.21

between CAI to REAL. This means that participants in CAI, VR, and REAL ended up with equivalent knowledge in ME except when comparing CAI to REAL where participants from the REAL condition gained more knowledge than did participants from the CAI condition. For the PBF process, Table 4.3a and Figure 4.5 show that the post-quiz scores did not significantly differ between VR to REAL, but they did significantly differ between CAI to VR and CAI to REAL. This means that participants when learning about PBF ended up with equivalent knowledge between VR and REAL, but ended up with higher knowledge from the VR and REAL than from CAI.

4.4.3. Effects on cognitive load by immersion for the different AM processes

Table Table 4.4 and Figure 4.6 key results of the analysis of cognitive load for each AM process across each condition.

Table 4.4: Highlighting the cognitive load experienced by participants for each dimension due to the condition and process variables

(a) General cognitive load as affected by the condition variable

Dimension	Estimate	F.value	t.ratio	p.value
Perceptual	-0.14	0.01	-0.31	0.752
Response	-0.5	1.34	-1.15	0.247
Spatial	-1.46	11.06	-3.32	< 0.001
Verbal	0.01	≈ 0	0.03	0.971
Visual	0.23	0.24	0.49	0.623
Auditory	-0.08	0.03	-0.17	0.863
Manual	-0.55	1.15	-1.07	0.284
Speech	-0.74	3.61	-1.9	0.058

(b) General cognitive load as affected by the process variable

Dimension	Estimate	F.value	t.ratio	p.value
Perceptual	0.71	3.01	1.73	0.083
Response	1.12	7.84	2.8	0.005
Spatial	0.37	0.86	0.93	0.353
Verbal	1.19	7.16	2.67	0.008
Visual	0.7	2.63	1.62	0.106
Auditory	1.16	6.95	2.63	0.008
Manual	0.09	0.04	0.2	0.835
Speech	0.22	0.37	0.61	0.538

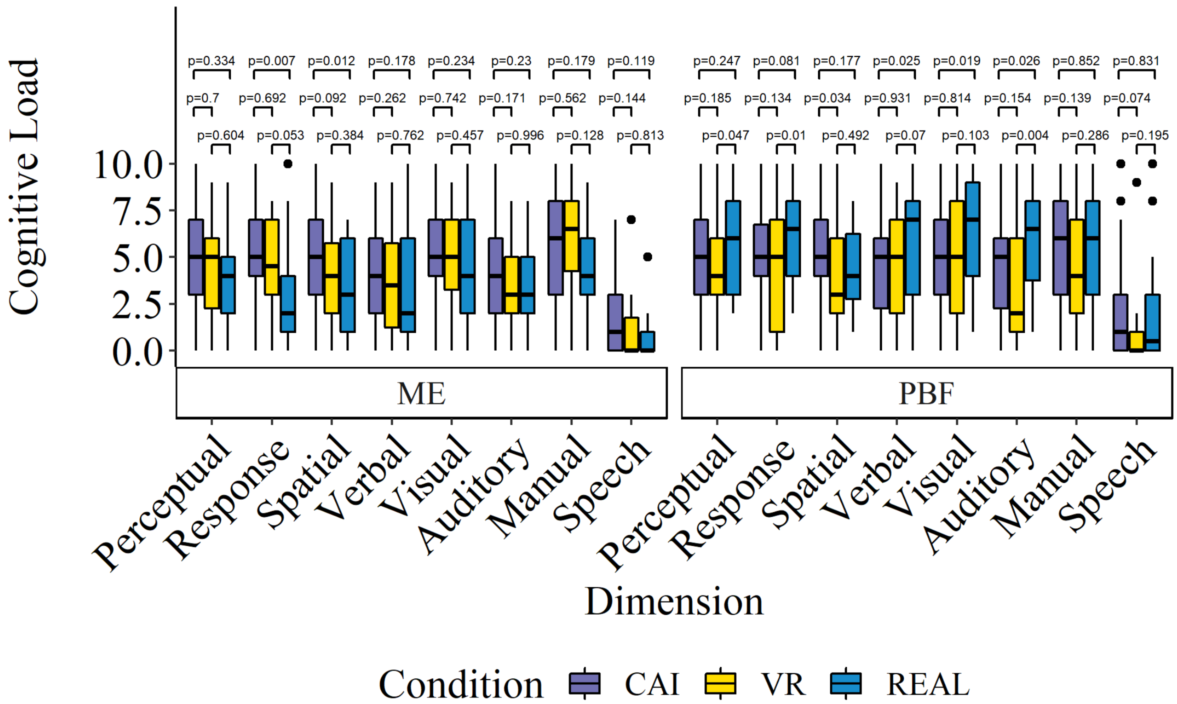


Figure 4.6: Showcasing the distribution of reported cognitive load as affected by the three conditions between the two AM processes

For this analysis, cognitive load was regressed on the centered variable for condition (CAI = -0.5, VR = 0, REAL = 0.5; between-subjects variable), and process (ME = -0.5, PBF = 0.5; between-subjects variable) and the interaction of these two variables (condition*process) as the covariates. This analysis also included a by-subject random intercept, utilized restricted maximum likelihood estimation to iteratively modify the parameter estimates to minimize the log-likelihood function, and evaluated this model with the Kenward and Rogers (KR) adjustment [175]. The following results reported from the analysis focus on each detailed effect when controlling for all other main effects and interactions in the model.

As can be observed from Figure 4.6, the main analysis showed no statistically significant effect on the overall cognitive load by condition such that on collapsing the process categories, participants generally reported equivalent cognitive load for each of the WPA dimensions between CAI, VR, and REAL. However, an exception in the analysis shows a significant effect of condition on the spatial dimension (Table 4.4a) where participants generally reported a significantly lower spatial cognitive load with the change in condition. The main analysis also showed no statistically significant effect on the overall cognitive load by process such that on collapsing the condition categories, participants generally reported equivalent cognitive load for each of the WPA dimensions between ME and PBF. However, the analysis shows a significant effect on the response dimension (Table 4.4b) where participants generally reported a significantly higher response, verbal, and auditory cognitive load for PBF than for ME.

To further understand the trends in the cognitive load between the conditions and AM processes, we conducted pairwise-comparison analyses between the different levels in condition and process. Table Table 4.5 shows that cognitive load generally did not significantly differ between the ME and PBF processes for the CAI and VR conditions, but response, verbal, visual, and auditory cognitive load in PBF was significantly higher than in ME from the REAL condition.

Table 4.5: Highlighting the cognitive load comparison between ME and PBF experienced by participants for each dimension from each condition

Dimension	Estimate	F.value	t.ratio	p.value	
Perceptual	CAI	0.3	0.56	0.75	0.454
Perceptual	VR	-0.27	0.1	-0.33	0.74
Perceptual	REAL	1.71	3.86	1.96	0.05
Response	CAI	0.15	0.17	0.41	0.679
Response	VR	-0.48	0.38	-0.61	0.537
Response	REAL	3.12	13.8	3.71	< 0.001
Spatial	CAI	-0.02	0	-0.05	0.956
Spatial	VR	-0.21	0.07	-0.27	0.786
Spatial	REAL	1.07	1.59	1.26	0.207
Verbal	CAI	0.02	0	0.04	0.96
Verbal	VR	0.77	0.76	0.87	0.384
Verbal	REAL	2.56	7.35	2.71	0.007
Visual	CAI	-0.3	0.52	-0.72	0.471

Dimension	Estimate	F.value	t.ratio	p.value	
Visual	VR	0.07	0	0.09	0.926
Visual	REAL	2.11	5.23	2.28	0.023
Auditory	CAI	0.2	0.23	0.48	0.627
Auditory	VR	0.23	0.07	0.26	0.79
Auditory	REAL	2.57	7.7	2.77	0.005
Manual	CAI	0.08	0.03	0.19	0.847
Manual	VR	-1.38	2.26	-1.5	0.133
Manual	REAL	1.12	1.28	1.13	0.257
Speech	CAI	-0.13	0.14	-0.38	0.702
Speech	VR	-0.25	0.13	-0.36	0.718
Speech	REAL	0.78	1.08	1.04	0.299

Figure 4.6 also shows that cognitive load for the ME process generally did not significantly differ between the conditions but spatial and response cognitive load from the REAL condition were significantly higher than cognitive load from the CAI condition. For the PBF process, however, cognitive load generally did significantly differ between the conditions in various pairwise comparisons. As shown in Figure 4.6, participants reported significantly lower spatial cognitive load from VR than from CAI and significantly lower response and auditory cognitive load from VR than from REAL. Additionally, participants reported significantly higher auditory, verbal, and visual cognitive load from REAL than from CAI.

4.5. DISCUSSION

The findings highlighted in Section 4.4 present key implications for the proposed research questions in this work. The following section elaborates on the interpretation behind the observed results and their underlying mechanisms.

How do the differences in immersion between CAI, VR, and REAL mediums affect knowledge gain when learning about ME and PBF?

Our collective findings in Section 4.4.2 reaffirm the existing knowledge gap in process-centric AM amongst designers and indicate that while any medium of instruction from this research can yield significant knowledge gains, differences in immersion between the conditions strongly affect knowledge gain when comparing learning between the different AM processes. Our analysis identified statistically significant differences in knowledge gain between the studied AM processes such that designers learning about PBF generally experienced a higher knowledge gain than designers learning about ME (32.3% higher). This trend was observed while accounting for the significantly higher pre-quiz knowledge in the ME group than in the PBF group with identical post-quiz knowledge in both AM process groups (Section 4.4.2.2). Paired with the findings on perceived prior awareness in AM from Section 4.4.1, these results indicate that there exists a knowledge gap amongst designers between ME and PBF with designers having more knowledge in more accessible processes like ME than knowledge in less accessible processes like PBF.

The results and analysis in Section 4.4.2.1 further identified a statistically significant effect of immersion on knowledge gain. Designers generally experienced a higher knowledge gain as the condition linearly changed from CAI to VR to REAL (20% higher). This implies that increased immersion can increase the knowledge gained from process-centric AM education. Specifically, however, designers did not experience a significant difference in knowledge gain across the mediums when learning about ME, but designers did show significantly higher knowledge gains when learning about PBF through VR and REAL than through CAI with no statistically significant difference in learning between VR and REAL. This means that immersion does not have a significant effect when learning about typically accessible AM processes like ME, but does have a significant effect when learning about typically inaccessible AM processes like PBF. This finding suggests that VR education can yield equivalent knowledge gains to REAL education while bypassing restrictions in introducing process-centric AM education for high-barrier-to-entry systems like PBF. VR instruction may hence offer industries an alternative to in-person education with higher knowledge gains during designer development than computer-aided instruction of typically high-barrier-to-entry AM processes.

How do the differences in immersion between CAI, VR, and REAL mediums affect cognitive load when learning about ME and PBF?

Our collective findings in Section 4.4.3 indicate that the differences in immersion generally do not strongly affect the mental effort experienced when comparing learning between different AM processes, but specifically have significant impacts within the different medium and AM process pairwise-combinations. This research limits the discussion of its findings to sight and motor-sensory information (i.e., limited to perceptual, response, spatial, visual, and manual cognitive load) as the verbal, auditory, and speech cognitive load dimensions were attributed to the design of the experimentation and not inherent to the mediums themselves. The analysis in Section 4.4.3 identified that designers generally experienced a significantly higher response processing cognitive load when learning about PBF than when learning about ME (11.2% higher). Specifically, however, Table 4.5 and Figure 4.6 show that the general trends in cognitive load observed are strongly influenced from REAL learning. Similarly influenced emerging and significant trends from REAL learning were observed in perceptual and visual processing cognitive load respectively (Table 4.5). These findings indicate that designers found learning about PBF to require more mental effort than learning ME when through REAL learning, but found virtual learning (i.e., through CAI and VR) about the two AM processes to require identical mental effort. For industries, this implies that virtual instruction, immersive or non-immersive, may yield lower mental effort exertion when learning about typically inaccessible and functionally complex AM processes like PBF.

The results and analysis in Section 4.4.3 also found that designers experienced a significantly lower spatial processing cognitive load (14.6% lower) as the medium of instruction changed from CAI to VR to REAL. Figure 4.6 shows that when compared to CAI learning, designers specifically experienced a significantly lower spatial cognitive load from REAL learning in the ME group and from VR learning in the PBF group with comparable effects between the two immersive mediums. Additional emerging and significant trends observed in Figure 4.6 for perceptual, response, and visual cognitive load support the finding that adding immersion to the learning experience can lower the mental effort exerted by designers during certain learning experiences. Specifically, our findings indicate that as the AM process changes from a functionally less complex process like ME to a more complex process like PBF, designers require less mental effort from immersive mediums than non-immersive mediums. This implies that designers may benefit more from immersive instruction than non-immersive instruction to lower exerted mental effort when learning about typically inaccessible and functionally complex AM processes like PBF.

4.6. CONCLUSION

The goal of this research was to identify the effects of immersion in the learning experience and study how immersion in different mediums of instruction (i.e., CAI, VR, REAL) affects the knowledge gain and the mental effort experienced when learning about different AM processes (i.e., ME, PBF). This research measured the pre-and post-quiz scores to study the knowledge gained from the experience and measured cognitive load using the WPA tool to study the mental effort experienced. The results in Section 4.4 indicate that immersion does not have a significant effect when learning about easily accessible and functionally less complex AM processes like ME, but does have a significant effect when learning about less accessible and functionally more complex AM processes like PBF. Immersion (virtual or physical) does not significantly affect knowledge gain when learning about ME; however, immersive mediums yield higher knowledge gains than non-immersive mediums when learning about PBF. Specifically, VR provides comparable knowledge gain of PBF concepts to REAL instruction while presenting a significant advantage in knowledge gain over CAI. Furthermore, physical immersion yields lower response and spatial cognitive load than immersive and non-immersive virtual instruction when learning about ME but yields higher response and visual cognitive load when learning PBF. Adding immersion to virtual instruction using VR further yields a lower spatial cognitive load when learning about PBF. The findings from this work have significant implications for using VR instruction to offer improved designer development in process-centric AM education as an alternative to in-person education and bypassing the restrictions in introducing process-centric AM education for high-barrier-to-entry systems like PBF.

While the findings from this research highlight significant differences between the three mediums (CAI, VR, REAL) in the knowledge gain and cognitive load when learning about different AM processes, these findings need to be considered with certain limitations of this work. Firstly, regarding the broader scope of this interdisciplinary work, this work limited its scope to observe large effect sizes within rudimentary AM learning experiences inspired by inductive teaching techniques often used in task- and problem-based learning in engineering and AM education [44,49,103]; however, this work did not use any specific pedagogical framework to design its intervention and teaching experiences. Future work needs to account for the effects of different learning styles and teaching methods on knowledge gain and experiential cognitive load. Additionally, the correlated effect of cognitive load on learning also needs to be further evaluated by considering how different cognitive load aspects affect learning [33] including how variations in modality and cueing across mediums of varying immersion affect learning [31]. Lastly, the designed virtual experiences, while identical to each other, were not validated by standards or specifications from literature [158]. Experiences within different forms of VR systems that vary in perceived immersion, interaction, sensory feedback, device modalities, and other VR specifications [158] may yield different learning and cognitive effects. Future work aims to check the different non-investigated items considered in the design of VR experiences on their effects on AM learning and experiential cognitive load.

Even within the specifics of this research, several limitations should be addressed in future work. This work did not filter participants by prior knowledge or ensure that prior knowledge was homogeneous before studying the effects of the intervention on knowledge gain and cognitive load. Rather, this work was aware of the limited formal AM education participants had before the study and hypothesized that the level of prior knowledge would be different between the two AM processes (i.e., ME and PBF) but homogeneous across the three conditions (i.e., CAI, VR, REAL) within each process. Although results from the pre-quiz indicated homogeneity in prior knowledge amongst the participants, future work should control for prior knowledge as a main independent variable and study how prior AM expertise can influence knowledge gain and cognitive load. Similarly, participants in the virtual conditions had significantly different comfort levels within their respective mediums; specifically, participants had a significantly higher comfort with CAI interaction than with VR interaction. Future work can account for such differences in skill and comfort on their effects on knowledge gain and cognitive load during learning. Knowledge gain in this work was measured using a pre-post quiz assessment and thus assumed to be short-term and linear in nature. This approach, however, limits the information collected as knowledge gain and does not assess other learning aspects such as transference and long-term retention. Future work could consider expanding the scope of defining knowledge gain and re-assess the effects of immersion on AM education. Additionally, the data collected was unevenly distributed and much smaller in size in the VR and REAL conditions. This is because a majority of this research was conducted during the COVID pandemic and as such, volunteers leaned toward virtual and remote participation than in-person participation. Future work can expand the current data set to further improve the resolution and power of these findings by collecting data from a larger and more evenly distributed sample of participants. Furthermore, this work did not investigate the novelty of VR over CAI learning to understand why VR learning yielded significant differences from CAI learning but identical effects to REAL learning for PBF. Future work aims to conduct in-depth qualitative studies including think-aloud exercises, interviews, and analysis of video and screen recordings to understand why learning experiences may yield the observed outcomes from this work. New knowledge from such future work can aid industries and further empower their designers to meet AM-driven product design needs for a range of AM processes.

Chapter 5

DIGITAL IMMERSION IN DFAM EVALUATIONS

5.1. INTRODUCTION

Iteration is an essential part of the design process as designers often go through several prototypes of their designs to solve engineering problems. Such prototypes often take the form of sketches, 3D models, or physical props. Physical prototyping, however, can be expensive and time-consuming [130,131], delaying progress to end-use products and solutions. Modern design and manufacturing processes therefore pay special attention to the digital artifact generation that precedes physical fabrication. Organizations leveraging additive manufacturing (AM) to address their end-use product needs are no exception to this. Although AM can reduce the time and cost of physical fabrication, these benefits only materialize when the digital 3D model is favorably designed for AM. The digital 3D modeling and design evaluation stages in the design process are therefore critical. This is because identifying and resolving potential issues with a design early on minimizes build failures and the cost of rework that follows. Designers must therefore know how to evaluate the manufacturability of their designs for the range of potential AM processes. For this purpose, possessing design for AM (DfAM) expertise is a must. However, designers generally lack this expertise, inhibiting them from taking advantage of the fabrication process [4,5,140,141]. Practicing DfAM during early design stages fosters the necessary intuition to acquire such expertise [104,142]. Design for AM intuition, therefore, is the designer's ability to evaluate and improve designs for manufacturability by AM by evaluating their opportunistic and restrictive characteristics. Therefore, honing this intuition is essential for designers to innovate with AM and solve complex engineering problems [11].

Possessing DfAM expertise requires distinct instruction on design and process-centric AM concepts, separate from instruction on other manufacturing processes [3,8]. Resources including worksheets [91–94], software tools [90,95,176,177], and visualized heuristics [96,97] provide DfAM guidance for this purpose. Because an artifact's design and its evaluations have historically been limited to computer-aided engineering (CAE) tools, designers are habituated to non-immersively evaluate digital designs for manufacturability. As a result, DfAM resources in literature have been modally designed for this established process, yielding digitally non-immersive resources when physical resources are not viable. A recent review of design and manufacturing processes, however, indicates the rise of immersive modalities in design processes for use in 3D modeling, virtual prototyping, and design evaluation [178]. This is because immersive virtual reality (VR) is shown to help designers better perceive the fit, form, and functionality of a design [108,109]. Such enhanced perception also improves the ability to identify errors and defects with 3D models [110,111]. With the advent of more affordable consumer-grade VR headsets, designers can now feasibly leverage the benefits of *immersiveness* in their design processes. However, little work examines varying presentations of DfAM knowledge, including presentations in digitally immersive modalities [98,99]. The benefits of immersion specifically on DfAM evaluations are therefore not well understood. There is a need to investigate how immersive DfAM evaluation affects the outcomes and effort associated with the act of evaluating designs. This research addresses this gap in the literature by leveraging established DfAM resources in immersive modalities and investigating the effects of immersion on DfAM evaluation.

Additive manufacturing encourages solutions with unique geometric complexity that are difficult to achieve with other manufacturing processes. This complexity often takes the form of organic, generative, or lattice structures that are uncommon in designs for subtractive manufacturing processes. Incorporating such complexity can be instrumental to the desired solution, but it can make the digital design difficult to evaluate for manufacturability. Given the 3D nature of geometric complexity, leveraging 3D spatial immersion in VR to aid DfAM evaluations seems more intuitive than using non-immersive CAE. However, before organizations use VR for this purpose research must establish how digitally immersive DfAM evaluations compare to their digitally non-immersive experiences and physical counterparts. This requires an investigation into how varying levels of immersion affect DfAM evaluation processes, which is currently lacking in the literature. The goal of this work is to, therefore, investigate the design of VR experiences for DfAM evaluations. For this purpose, Section 5.3 describes the method of study used to address the research questions and Section 5.4 presents the results from the study. Additional details on the findings and their implications are then discussed in Section 5.5, with Section 5.6 summarizing the collective contributions of this work and its limitations for future work. The contributions of this work have significant implications for how future designers are trained in DfAM to meet the AM demands in the workforce.

5.2. RESEARCH QUESTIONS

This research aims to investigate how immersion affects experiences involving the DfAM evaluation of 3D models. For this purpose, this research implements a mixed methods study with a sequential explanatory design. In other words, the study first extracts quantitative information and then qualitative information on the observed effects. Such an investigation offers a general understanding of the trends that exist as well as insight into the underlying mechanism behind these trends. The following research questions (RQs) guide this investigation:

Research Question 1. *How do the differences in immersion between CAE, VR, and REAL modalities affect the outcomes of DfAM evaluations of designs of varying manufacturability?*

This research question identifies the effects of immersion on DfAM evaluation outcomes by examining the trends in quantitative data. Specifically examined are 1. the DfAM score of the design, 2. the time taken for the evaluation, and 3. the confidence of the evaluation. Compared to the CAE evaluation, it is hypothesized that the VR and REAL evaluations will yield scores closer to expert scores from faster and more confident evaluations. However, no significant differences between the two immersive modalities are expected. Such trends are hypothesized due to expected enhancements in spatial perception and reasoning within immersive modalities [108–111]. Effects on DfAM reasoning from the perceived complexity of the evaluated designs are also expected. Specifically, the difference in outcomes between the immersive and non-immersive evaluations is expected to increase for designs with higher perceived complexity [108,109].

Research Question 2. *How do the differences in immersion between CAE, VR, and REAL modalities affect the cognitive load experienced when evaluating designs of varying manufacturability?*

This research question extracts further quantitative insight into the effects of immersion on completing DfAM evaluations. Specifically examined is the numeric, self-reported, cognitive load experienced by the designers during the evaluation. Unlike RQ 1, this research question focuses on the effort required to complete the *entire* DfAM evaluation exercise. This approach is synonymous with design processes where designers must make conclusions about the design from iterative evaluations using the same modality. Compared to the CAE experience, it is hypothesized that the VR and REAL experiences will generally yield lower reported cognitive load values. However, no significant differences between the two immersive modalities are expected. It is expected that the effort required to perform design evaluation operations, and thus the cognitive load, changes due to the change in immersion. Specifically, evaluations within modalities that require low effort will yield lower reported cognitive load than those that require high effort [83,84,87,88]. Such variation in effort is expected to arise due to differences in immersion, the perceived complexity of the designs, and the required engagement with the designs.

Research Question 3. *How do the differences in engagement between CAE, VR, and REAL modalities explain the observed trends in DfAM evaluation outcomes and cognitive load?*

This research question dives into the mechanics of completing DfAM evaluations within varying levels of immersion by examining qualitative data. Specifically, the designer's active and passive engagement with the designs during the DfAM evaluation is observed. Given that designers are studied in similar environments, it is hypothesized that analyzing how they engage with the designs will explain the trends observed in RQ 1 and RQ 2. This is expected because when other factors are controlled, the differences between groups can likely be attributed to their modality. Specifically, attributed to how immersion alters the perception of 3D artifacts and other visual information [31,65] and influences the interactions involved. As an explanatory research question, the goal is to establish a basic understanding of how designers interact with and evaluate designs for AM within varying levels of immersion. Such insight lays the groundwork for future hypothesis-driven research into utilizing different modalities for DfAM problem-solving.

5.3. METHODOLOGY

This research was motivated to observe the role of immersion in cultivating a designer's DfAM intuition under given printing constraints. Specifically, to understand how immersion affects a designer's evaluation of different designs for their manufacturability with AM at specific print orientations and process parameters. The goal of this research was to, therefore, identify the effects of immersion on DfAM evaluation when evaluating designs of varying manufacturability.

Designers assessed manufacturability for material extrusion AM through either the CAE, VR, or REAL modality. Although print orientation and process parameters affect a design's manufacturability, through outcomes such as print time, support usage, etc, this research focused on studying circumstances that resemble a visual check of the design *before* calculating such manufacturability outcomes. Such an investigation informed on the role of immersion in the designer's reasoning and thinking process during DfAM evaluations. A mixed-methods study of their experiences was conducted using a sequential explanatory design, i.e., a quantitative phase followed by a qualitative phase. The design of the experiments for both phases was similar, except for a think-aloud task included in the qualitative phase during the DfAM evaluation exercise. This think-aloud data from every participant's perspective explained their engagement with the designs and contextualized the general trends observed in the quantitative results.

The designed experiment required completing the steps illustrated in Figure 6.1. All these steps were completed on an online Qualtrics survey. This includes presenting questionnaires, instructions, and the CAE and VR digital tools for the DfAM evaluations. No personal or identifiable information was collected from the participants. Completing the survey corresponded to opting in for the study; not doing so was registered as *opting out* of the study. Participant data was deleted accordingly as per the approved Internal Review Board (IRB) protocol.

Section 5.3.1 describes the process of using the survey to assign participants to the study conditions and ask about their backgrounds. Specifically, their background in AM, material extrusion (ME), design for ME (DfME), and proficiencies with CAE and VR. These were all recorded on a 5-point Likert scale. After sharing their backgrounds, participants were introduced to their assigned modality and a tutorial. The goal of this tutorial was to provide familiarity with the modality and the DfAM evaluation exercise. Doing so helped minimize the effects of technological proficiency on the measured outcomes in the study.

Participants assigned DfAM scores to one design during the tutorial and three designs during the main study. These designs came from a set of six pre-selected 3D models. Section 5.3.2 shows this set of designs and explains the expert review process used to select them. For the main study, each design was evaluated one at a time, in a pre-determined counterbalanced order as further explained in Section 5.3.3. For this DfAM exercise, each evaluation was measured on three outcomes: 1. the design's DfAM score, 2. the time taken for the evaluation, and 3. the confidence of the evaluation. The DfAM score was the calculated sum of eight distinct process-agnostic metrics. These metrics were consolidated from past work [91,92] into a worksheet [165] that was provided for DfAM evaluations. Each metric was evaluated on a 3-point Likert scale, corresponding to a *low-medium-high* scale. Designs therefore received a DfAM score between 8-24 points, with a higher score suggesting higher manufacturability with ME. Participants in the qualitative method group were additionally asked to think aloud during the DfAM exercise (see Section 5.3.4). Only three designs were presented to minimize the effects of survey fatigue. Doing so retained focus on the cognitive load directly impacted by the exercise of evaluating designs within their assigned modality.

Upon completing evaluations for three designs, participants reported the cognitive load they experienced from the exercise. Section 5.3.5 explains how this data was collected with a self-reported Workload Profile Assessment (WPA) [172]. The tool measured the cognitive load exerted during the experience across eight dimensions. Each dimension was scored between 0 and 10 to represent their cognitive load. This data offered context to the effort required for completing the DfAM evaluation exercise within each modality. Pairing this information with that derived from the DfAM exercise data holistically demonstrates how varying levels of immersion affect DfAM processes.

Pre-study procedure
Distribute participants between the modalities
Assess their background with AM, VR, etc.

↓

Complete a tutorial on DfAM
Practice a DfAM evaluation for one design in the modality
Compare the evaluation to an average expert's

↓

Complete the DfAM exercise
Evaluate three designs for manufacturability by AM
Think-aloud sessions are video and audio recorded

↓

Post-study procedure
Report cognitive load experienced from the DfAM exercise

Figure 5.1: Illustrating the steps for the designed mixed-methods experimentation

5.3.1. Pre-study procedure

Participants in this research were second and third-year undergraduate students. They were recruited from an engineering design methodology course at an R1 university. All students were informed of their rights and options as per IRB protocol before conducting the study. Those who *opted in* to participate were given an online Qualtrics survey to use for their participation in the study. Hidden from the participants, the survey's built-in algorithm balanced assignments evenly between the three conditions: CAE, VR, or REAL. Once assigned to a condition, participants answered a questionnaire, describing their knowledge of 3D printing. This data encapsulated their general experiences with AM and their specific experiences with the ME process and DfME practices. Collectively, this data indicated the need to account for prior knowledge in the statistical analysis of the measured outcomes in the study. Knowledge in AM, ME, and DfME was recorded on the following 5-point Likert scale:

1. I have never heard or learned about this topic before this
2. I have some informal knowledge on this topic
3. I have received some formal knowledge on this topic
4. I have received lots of formal knowledge on this topic

5. I am an expert on this topic

After sharing their prior knowledge of 3D printing, participants in the CAE and VR conditions described their proficiency with their assigned modality. Those in the REAL condition were not asked for any such proficiency. As relevant to the study, the questionnaire specifically inquired about their proficiency in working with or interacting with 3D models. This data served to establish the need for a tutorial phase for each condition before the main study. This is because the participants likely had much more experience working in CAE and REAL modalities than in VR. An on-par comparison of DfAM processes between the conditions necessitated a tutorial, requiring empirical evidence for support. Therefore, it was important to measure and acknowledge this difference in technological proficiency. Proficiency in CAE and VR was recorded on the following 5-point Likert scale:

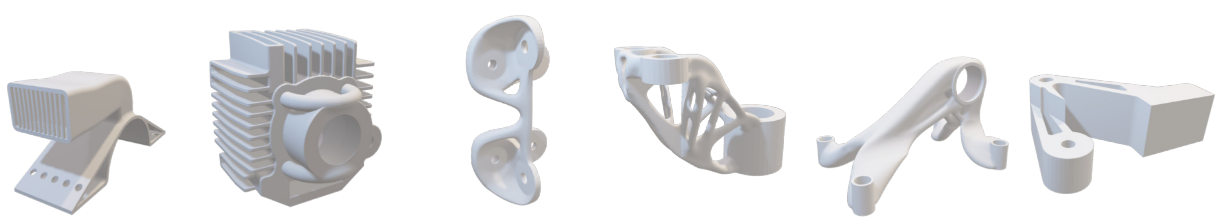
1. I have never worked with 3D models in this modality before this
2. I am slightly comfortable working with 3D models in this modality
3. I am comfortable working with 3D models in this modality
4. I am extremely comfortable working with 3D models in this modality
5. I am an expert on working with 3D models in this modality

Upon completing the questionnaire, participants were introduced to their assigned modality. Those assigned to the CAE condition were directed to the evaluation activity via a link on their computers. Those in the VR and REAL conditions were directed to designated areas that were set up with the resources required for their respective conditions. Participants in the VR condition were each given a Meta Quest headset and controllers and directed to the evaluation activity on the Meta Quest Browser app. Participants in the REAL condition were directed to a table with the physical parts where they continued the survey. The physical parts were manufactured using ME and underwent multiple post-processing cycles of coating with primer and sanding. Doing so minimized any visible indications of the original fabrication process, minimizing biased evaluations. Once at their designated areas, participants proceeded to the tutorial: a practice DfAM evaluation exercise designed to familiarize them with their assigned modality.

5.3.2. Selecting 3D models

The goal of the design selection process was to identify a set of designs that *truly* varied in their DfAM scores. This is because this research aimed to identify the effects of immersion on DfAM evaluation when evaluating designs of varying manufacturability. Studying designs with identical DfAM scores could inhibit isolating the effects of immersion on the measured outcomes [99]. For this purpose, this research first identified a set of designs to use for the main study through an expert review process. Six experts with 4-10 years of demonstrated AM and DfAM expertise in academia and industry reviewed twelve different designs pre-selected by the authors. The experts carried out the same DfAM evaluation exercise prepared for the main study for each design. This means each design was evaluated using eight metrics on a 3-point Likert scale [165]. The sum of these was an expert-established DfAM score, with a higher score indicating higher manufacturability.

To optimize the sample size for statistical analysis, only six of the designs from the original twelve were selected for the main study (see Figure 5.2 and Ref. [179]). For this selection, the designs were roughly grouped into low, medium, and high-scoring designs. *Lows* were scored roughly between 8-13, *mediums* between 14-18, and *highs* between 19-24. Two designs from each group were selected, specifically, those that varied the most in their DfAM scores between the groups. There was a significant difference in DfAM scores between the low group (D1, D2) and the high group (D5, D6). The differences from the medium group (D3, D4) were not as significant but still observable and therefore included in the main study.



D1 (11.8) D2 (13.5) D3 (17.5) D4 (17.5) D5 (20) D6 (21.3)

Figure 5.2: Displaying the designs selected for the DfAM evaluation exercise (with their expert-assigned DfAM scores)

5.3.3. The DfAM exercise

The goal of this research was to observe how varying levels of immersion affect DfAM evaluations. As a result, participants were tasked with evaluating 3D models for manufacturability in either the CAE, VR, or REAL modality. Each condition included three key features to aid the DfAM evaluation: 1. virtual or physical 3D models, 2. tools for measuring and evaluating the designs, and 3. digital instruction on completing the exercise. To ensure that the exercise was similar across the conditions, all the digital and physical features were made identical. Figure 5.3 presents the designed environments for each condition to demonstrate this.

As shown in Figure 5.3, participants were instructed identically to evaluate the designs for manufacturability in a pre-defined, but not necessarily optimal, print orientation. They were reminded to consider the ME process during the design's evaluation. Free interaction with a design and its environment was permitted to encourage intuitive exploration of the designs. As such, typical engagement in VR and REAL included picking up, rotating, and moving the models to get a good view of the design. Those in CAE manipulated the camera by zooming, orbitally rotating, and panning for the same purpose. Each modality afforded interactions that compensated for its inherent limitations, enabling similar experiences across the modalities. Designs were also presented at a fixed scale in all the modalities. Therefore, rescaling or digitally enlarging the 3D model in CAE and VR was not permitted. This means that the dimensions of the digital models matched those of the physical objects, ensuring identical comparisons between the modalities.

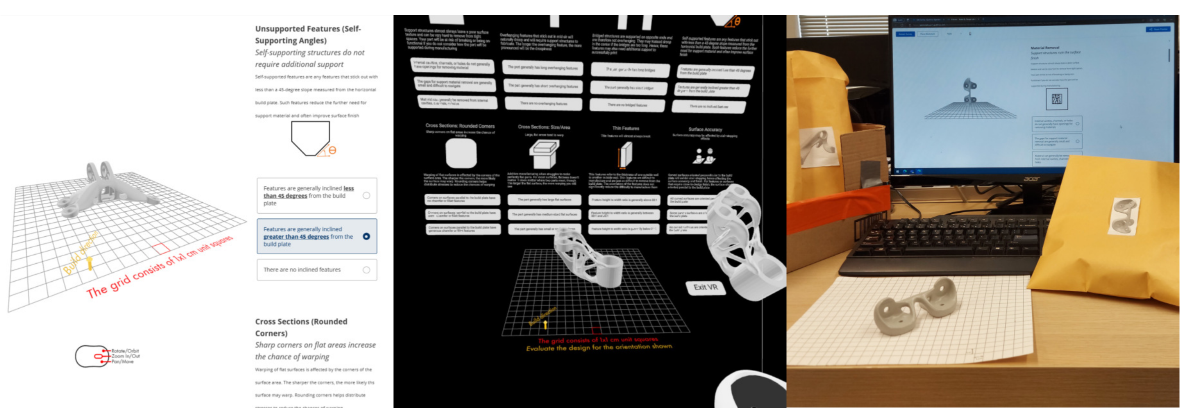
While evaluating designs on DfAM, participants used a worksheet [165] with eight metrics derived from past work by Booth et al. [91] and Bracken et al. [92]. These metrics corresponded to the following eight DfAM concepts:

1. Removal of support structures
2. Presence of unsupported overhangs
3. Presence of unsupported bridges
4. Presence of self-supporting features

5. Sharpness/Rounding of cross-sections
6. Size/Area of cross-sections
7. Thinness of features compared to the print resolution
8. Surface finish on non-build direction curved surfaces

Each metric was evaluated on a 3-point Likert scale, resulting in a sum score of 8-24 points for each design. For the main study, participants were not informed of these DfAM scores. However, during the tutorial, they were offered a comparison of their evaluation with an expert's. This means that participants were treated like experts in the main study and were not provided with any feedback on their evaluation.

Participants concluded one evaluation by filling out the entire worksheet and reporting their confidence in the design's evaluation. They completed the entire exercise by evaluating three designs, one at a time. Limiting evaluations to three designs minimized the effects of survey fatigue. This retained a focus on studying the cognitive load experienced directly from completing the DfAM exercise within their assigned condition. The three designs presented were arbitrarily assigned from six possible options (see Section 5.3.2). A 6x6 Balanced Latin Square was generated and split into two 6x3 tables, presenting 12 distinct orders to use for the study. These orders were counterbalanced, thus, minimizing immediate sequential or carry-over effects [180].



(a) CAE setup (b) VR setup (c) REAL setup

Figure 5.3: Presenting the design of the DfAM evaluation environments for each condition. Each environment included a 3D artifact, tools for evaluating the design, and instructions for completing the exercise

5.3.4. Think-aloud protocol

The goal of the think-aloud task was to understand the participants' engagement with the designs during the DfAM evaluation exercise. For this purpose, the following think-aloud protocol was implemented for the experiment:

- The task was untimed and participants were encouraged to take their time evaluating the designs.
- Participants were prompted to explain *"What about the design rationalized the option(s) you[participant] chose on the DfAM worksheet?"*.
- They were instructed to verbalize all their thoughts as frequently as possible.
- If they were silent for more than 30 seconds, they were reminded to *think aloud* and continue.

To collect think-aloud data, each participant's session was video and audio-recorded. Participants were informed of this recording and were asked to re-confirm their consent before proceeding. Those who changed their consent were not recorded and were excluded from the study. The video and audio recordings were later coded together to extract the think-aloud data. Two expert raters (from the authors) coded all the recordings using these codes in DARMA, a joystick-driven, dual-axis rating tool for videos [181]. To clarify coded versus uncoded content, raters moved the joystick to the extremes of the axes when assigning codes to the recordings. Doing so ensured that the coded data was distinguishable from the uncoded data. The final two-dimensionally coded data was used to explain the participants' engagement with the designs during the DfAM evaluation exercise.

A deductive coding approach was used to analyze the think-aloud data. Themes were deduced based on work by Lauff et al., which informs on how designers engage with artifacts in design processes [28]. Specifically, how designers actively and passively engage with artifacts. These themes expand upon their roots in design communication [182,183] and are similarly utilized in past work with 3D artifacts and VR contexts [184,185]. Based on these thematic distinctions, *Engagement* in this work was defined as *active* and *passive* interaction with the designs. Active engagement corresponded to *direct* interactions with the

3D objects. This included picking up, rotating, and moving the models to get a good view of the design. Passive engagement corresponded to *indirect* interactions with the 3D objects or making contextual references to the designs. Pointing at the design and its features without *intentionally manipulating* the model was considered indirect interaction. Emphasizing aspects of the design that were related to AM or DfAM concepts was considered contextual referencing.

The two codes established with these themes in mind were *Referencing* and *Interacting* (see codebook in Table 5.1). These corresponded to *passive* and *active* engagement with the designs respectively. In DARMA, the code *Interacting* was assigned to the axial ends of the x-axis to signify active engagement. Similarly, *Referencing* at the ends of the y-axis signified passive engagement. Axial polarity was irrelevant to the coding process and codes were standardized to the same quadrant for analysis. The center of the axes was assigned as *No Engagement*. This was used to signify the absence of any engagement with the designs and account for time spent on other unrelated tasks. The coding process was on a continuous timeline, meaning recordings were not segmented or discretized. The codes were not mutually exclusive and were assigned to the same time point if appropriate. This means that every time point in the recording corresponded to *No Engagement*, *Referencing*, and/or *Interacting*, and no point was left uncoded.

Table 5.1: Codebook used to analyze the video and audio recordings and identify emerging themes

Code	Description	Example
Referencing	General expressions or actions on recognizing shapes and features, picturing or imagining features and objects, or making estimations and assumptions to aid in evaluative decision-making	"This clearly has a lot of overhanging features" "I don't think I see any bridged features" "I can see these overhangs over here needing a lot of support material, but it should be easy to remove" "I think these look twice as high as they are wide"

Code	Description	Example
Interacting	General and intentional actions to manipulate the 3D model (or move around the 3D model) to evaluate it from different perspectives	Observable manipulation within or of the environment or the 3D model with a *clear intention to evaluate the design* (i.e., not simply fidgeting with the model or environment)

5.3.5. Gauging cognitive load

After completing the design evaluation exercise, participants reported their cognitive load. They used the Workload Profile Assessment (WPA) tool [172] to quantify the cognitive load they experienced. Compared to the Subjective Workload Assessment Technique and the NASA Task Load Index, the WPA's higher sensitivity was preferred for such quantitative assessments [186]. Participants scored eight workload profile dimensions between 0 and 10 to represent their mental exertion. These eight dimensions spanned Perceptual, Response, Spatial, Verbal, Visual, Auditory, Manual, and Speech cognitive processing needs. Participants received a text and audio description of each dimension to review, along with an example of each dimension applied in practice.

Using these descriptions, participants assessed their cognitive load and assigned appropriate values to each dimension, one at a time. The *Verbal* and *Auditory* dimensions, though not directly applicable to the design DfAM exercise, were included to ensure consistency with the WPA tool. This is because the designed experiment did not study any tasks or elements that gave verbal instruction and audio cues. However, the WPA tool was designed to study tasks that would include such elements. The *Speech* dimension was also included under the same rationale. Although the think-aloud task in the qualitative method group induces *Speech* processing cognitive load, this research limits measurements of mental exertion to the quantitative method phase. Additionally, this research did not check or correct for any misinterpretations of the dimensions by the participants. Therefore, the inclusion of these dimensions ensured that all the necessary information was collected to study the cognitive load experienced by the participants.

5.4. RESULTS

This research conducted a mixed-methods study to evaluate the effects of immersion on DfAM evaluation and experiential cognitive load. To statistically explain the background data and the cognitive load data, linear regression models (lm) were generated. Linear mixed-effects regression modeling (lmer) was used to statistically analyze the DfAM evaluation data. Pairwise comparisons between variables were done using Estimated Marginal Means tests. The *lmer* utilized restricted maximum likelihood estimation to iteratively modify the parameter estimates with a minimized log-likelihood function. The *lm* and *lmer* model assumptions were checked using the Peña and Slate [173] and the Loy and Hofmann [174] procedures respectively. Unless otherwise specified, this research did not find any observable violations and relies on the acceptable range for the robustness of the respective regression models. A 95% confidence interval was used to determine statistical significance (i.e., $p < 0.05$). The p-values from the *lmers* are adjusted using the Kenward and Rogers adjustment to account for the small sample size. Those from the pairwise comparisons were adjusted using the Bonferroni method to account for multiple comparisons. All potential outliers in the data were retained in each analysis. The reported findings are presented in the following format: $b = 0.00$, $F(n,m) = 0.00$ $[t(n,m) = 0.00]$, $p = 0.00$. Here, b is the regression coefficient (i.e., slope), F is the F-statistic, t is the t-statistic, and p is the p-value. The n and m values represent the degrees of freedom for the numerator and denominator respectively.

5.4.1. Background analysis

The study included 124 participants between two method studies: Quantitative and Qualitative. As shown in Table 5.2, they were evenly distributed in each method across the three conditions: CAE, VR, and REAL. Note that Table 5.2 lists only the participants who completed *all* the required tasks of the study for their method group. Also, note that only participants in the qualitative method group conducted the think-aloud task during the DfAM exercise. The distribution in Table 5.2 was uniform within acceptable margins, strengthening the statistical analysis of the measured outcomes.

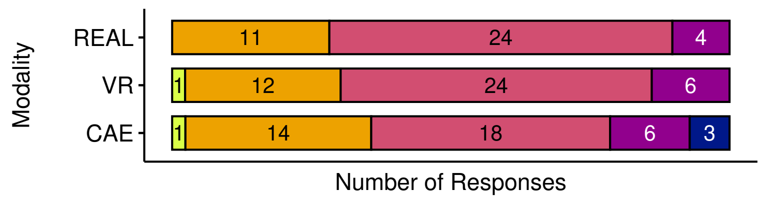
Analyzing the participants' prior knowledge of AM, ME, and DfME concepts helped account for the effects of such knowledge on the measured DfAM outcomes and cognitive load. For the analysis, the distributions of the prior knowledge in AM, ME, and DfME were regressed on the centered condition (CAE= -0.5, VR= 0, REAL= 0.5). The results showed no observable significant difference between the three conditions in their prior knowledge of AM, $b = -0.09$, $F(1,122) = 0.26$, $[t(1,122) = -0.51]$, $p = 0.612$, of ME, $b = -0.19$, $F(1,122) = 0.78$, $[t(1,122) = -0.88]$, $p = 0.38$, and of DfME, $b = -0.15$, $F(1,122) = 0.47$, $[t(1,122) = -0.69]$, $p = 0.493$. This trend can be observed in Figure 6.4, where participants in all the conditions reported similar prior knowledge of AM, ME, and DfME. Specifically, they shared that they generally had *some informal knowledge* of each of the topics.

Participants in the CAE and VR conditions also described their proficiency with their respective modalities. Analyzing this data established the need for a tutorial phase for each condition before the main study. The collapsed technology proficiency was regressed on the centered condition (CAE= -0.5, VR= 0.5). As expected, participants generally showed a significantly higher proficiency for CAE technology than for VR technology, $b = -1.66$, $F(1,83) = 45.74$, $[t(1,83) = -6.76]$, $p < 0.001$. Specifically, participants in the CAE condition were generally *extremely comfortable* with CAE technology; however, those in the VR condition had generally *never worked with* VR technology. This trend shown in Figure 5.5 was expected because students had likely completed CAE/CAD course requirements but likely not any VR coursework. Although expected, the trend supports the need for a tutorial on working in VR. Such a tutorial balances the technological proficiency between the conditions before the main

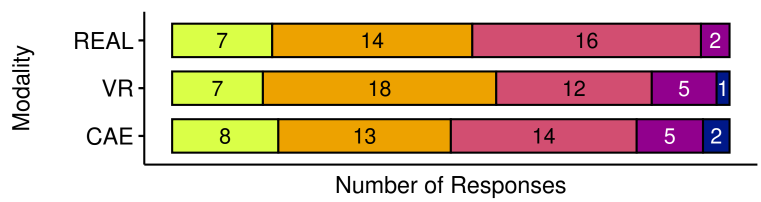
DfAM study.

Table 5.2: Displaying the distribution of participants between the methods of study and the conditions

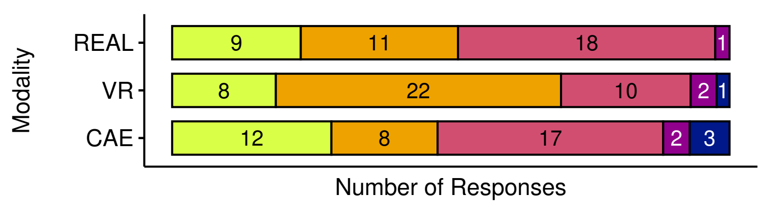
	CAE	VR	REAL
Qualitative	11	10	10
Quantitative	31	33	29



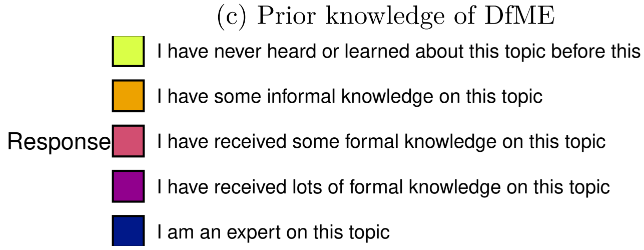
(a) Prior knowledge of AM



(b) Prior knowledge of ME



(c) Prior knowledge of DfME



(d) Common legend for responses

Figure 5.4: Presenting the distribution of reported prior knowledge on AM, ME, and DfME between the conditions

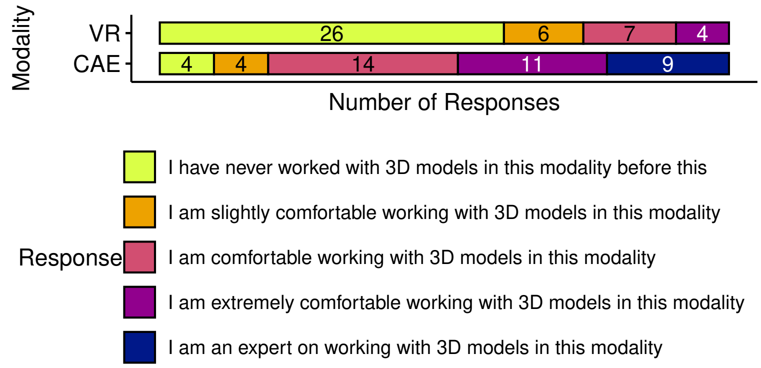


Figure 5.5: Presenting the distribution of reported proficiency on working with CAE and VR modalities

5.4.2. DfAM outcomes

Results presented in this section are observations of the quantitative method group only. This group did not conduct the think-aloud task during the DfAM exercise and consisted of only 93 participants. Analyzing the data collected from this group helped tackle the first research question, i.e., identifying the effects of varying levels of immersion on DfAM outcomes. For this analysis, the DfAM score, evaluation time, and reported confidence were regressed on the centered variables for *Condition*, and *Design* as a covariate. *Condition* served as a between-subjects variable centered around the three studied conditions: CAE = -0.5, VR = 0, REAL = 0.5. *Design* served also as a within-subjects variable centered around the six designs: D1 = -0.5, D2 = -0.3, D3 = -0.1, D4 = 0.1, D5 = 0.3, D6 = 0.5. Each participant's unique ID (*PID*) served as a random intercept to control for non-independence of observations. The presented results from the regression analysis focus on each detailed effect when controlling for all other main effects in the model. Only the interaction effects between condition and design were considered in the analysis.

The main analysis showed no significant effect of *Condition* on the *Score*, *Time*, and *Confidence* (see Table 5.3a). As seen in Figures 6.7a, 5.8, and 5.9, participants generally reported similar scores, experienced similar evaluation times, and were equivalently confident across the modalities. The main analysis also showed no significant effect of design on *Time* and

Confidence but showed a significant effect on the DfAM scores (see Table 5.3b). Specifically, on collapsing *Condition*, participants reported significantly higher DfAM scores as the designs changed from D1 to D6. Figures 6.7a, 5.8, and 5.9 show that participants identified significant differences between the designs themselves regarding their manufacturability by ME, with similar amounts of time and confidence. This means that the selected designs were suggestive of varying DfAM scores and that participants could intuit this.

Estimating a two-way interaction between *Condition* and *Design* explained how the effects of the modalities on the DfAM outcomes varied with the designs. The analysis showed a significant effect from the interaction between *Condition* and *Design* on *Score*, but not on *Time*, and *Confidence* (see Table 5.3c). Specifically, the effect of *Condition* on *Score* decreased as the value of *Design* changed from D1 to D6. Figure 5.6 illustrates this interaction effect where the direction of the effect of *Condition* on *Score* flips from D4 to D6. In other words, the DfAM scores from the CAE condition go from being lower than the VR and REAL scores to being higher than them. This means that a modality's effect on the DfAM scores was dependent on the design being evaluated.

A secondary analysis was conducted to understand the effects of *Condition* and *Design* on the difference between the DfAM scores assigned by participants and the expert scores. This analysis showed no significant effect of *Condition* on the difference between scores, $b = 0.39$, $F(1,91) = 2.09$, $[t(1,91) = 1.45]$, $p = 0.152$, but showed a significant effect of *Design* on the difference, $b = 0.64$, $F(1,267) = 4.79$, $[t(1,267) = 2.19]$, $p = 0.029$. Specifically, on collapsing *Condition*, DfAM scores assigned by participants generally deviated further from the expert scores as the designs changed from D1 to D6. This means that although participants could identify differences in the designs' manufacturability, they could not evaluate them as well as the experts. That is participants under or over-estimated the expert scores by similar amounts across the conditions, which worsened as the designs changed. The estimated two-way interaction between *Condition* and *Design* showed no significant effect on the difference between scores, $b = 0.3$, $F(1,263) = 0.17$, $[t(1,263) = 0.41]$, $p = 0.679$. This means that the effect of *Condition* on the difference between scores was not dependent on the design being evaluated.

Table 5.3: Listing the different experimental variables and their statistical effect on the DfAM outcomes

(a) Effect of *Condition*

Outcome	Estimate	n.df	df	F.value	t.ratio	p.value
Score	0.03	1	91	0.01	0.08	0.936
Time	-0.24	1	91	1.28	-1.13	0.261
Confidence	-0.90	1	91	2.70	-1.64	0.104

(b) Effect of *Design*

Outcome	Estimate	n.df	df	F.value	t.ratio	p.value
Score	4.04	1	257	134.54	11.60	0.000
Time	0.01	1	254	0.00	0.03	0.974
Confidence	0.04	1	195	0.04	0.20	0.838

(c) Effect of the *Condition* and *Design* interaction

Outcome	Estimate	n.df	df	F.value	t.ratio	p.value
Score	-2.14	1	252	6.32	-2.51	0.013
Time	-0.20	1	249	0.18	-0.42	0.675
Confidence	0.50	1	194	1.05	1.02	0.307

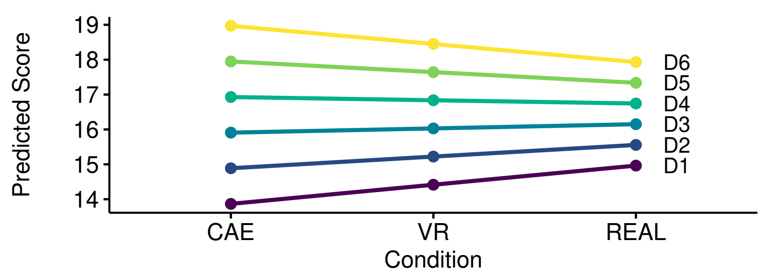


Figure 5.6: Illustrating the interaction between the effects of condition and design on the DfAM scores

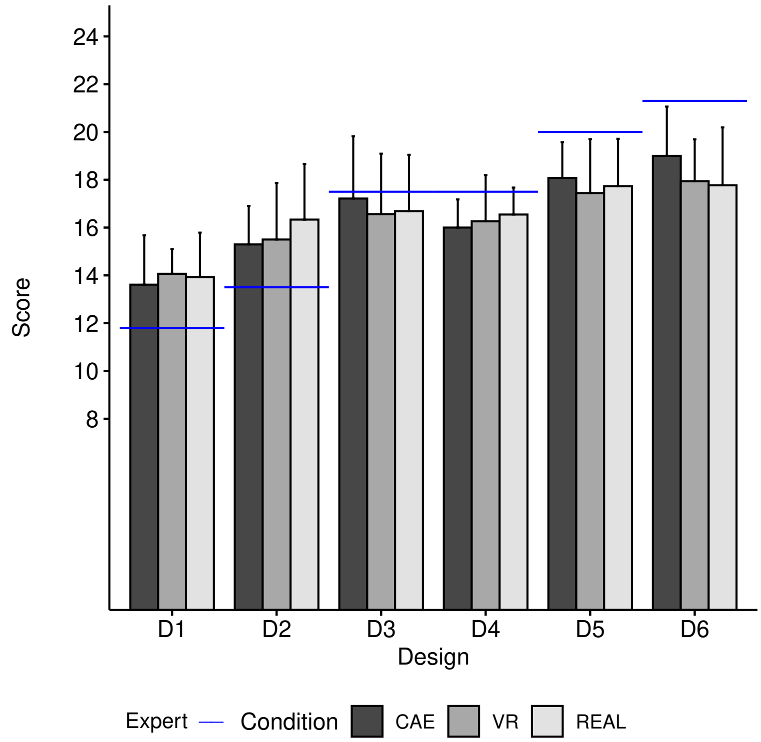


Figure 5.7: Illustrating the DfAM scores assigned for each design across the conditions. A comparison to a condition-independent expert score for each design is also presented

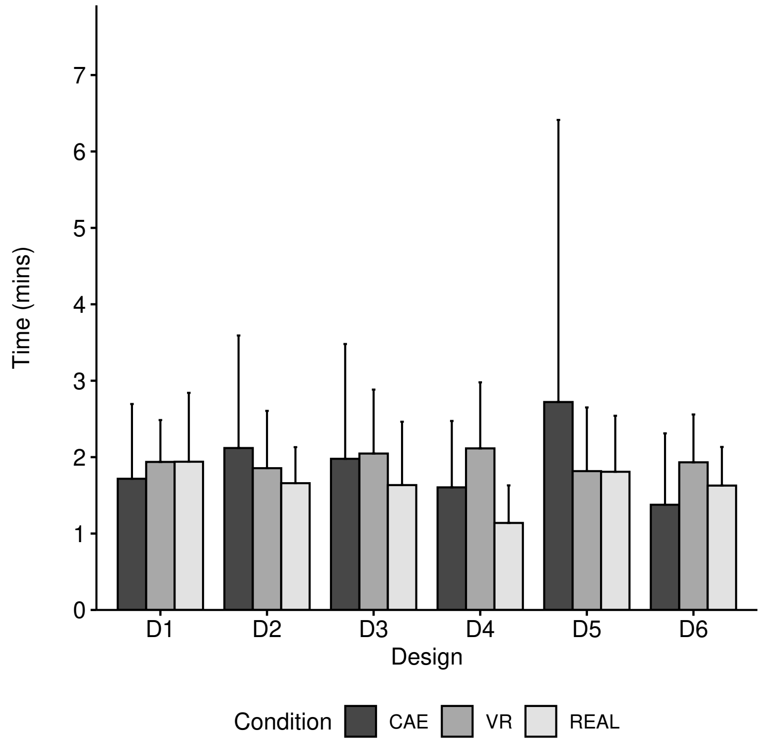


Figure 5.8: Illustrating the time taken by participants to evaluate each design across the conditions

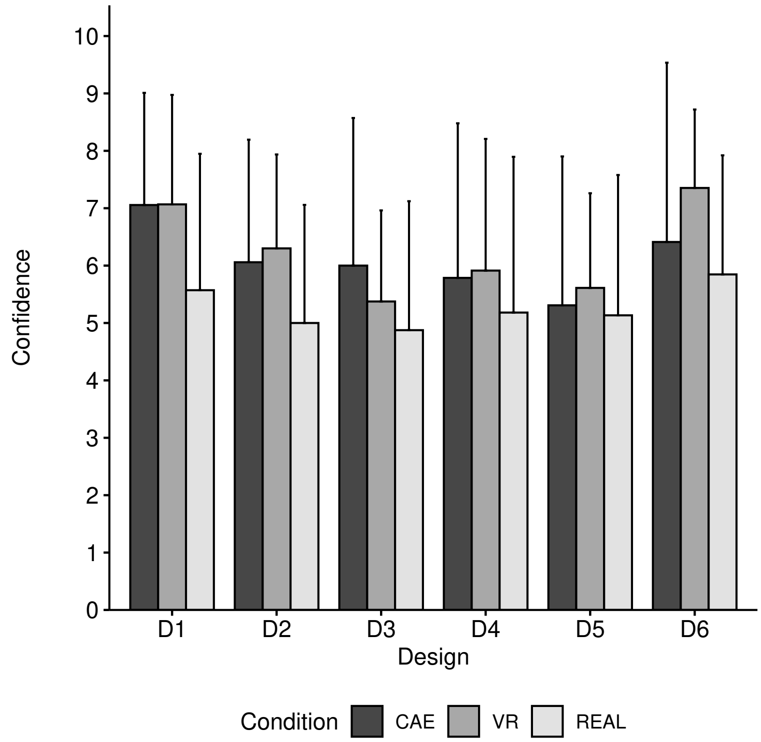


Figure 5.9: Illustrating the confidence expressed on the DfAM evaluation for each design across the conditions

5.4.3. Cognitive load

Results presented in this section are also observations of the quantitative method group only (i.e., from 93 participants). Analyzing the data collected from this group helped tackle the second research question, i.e., identifying the effects of varying levels of immersion on cognitive load. Checking the assumptions for linear regression modeling showed violations of normality in the data for the *Auditory* and *Speech* dimensions. These are sensible violations because the *Auditory* and *Speech* dimensions did not apply to the DfAM exercise. In addition to the *Verbal* dimension, these dimensions were excluded from the analysis and the reported findings. For this analysis, the *remaining* five dimensions of cognitive load were regressed on the centered variable for *Condition*. *Condition* served as a between-subjects variable centered around the three studied conditions: CAE = -0.5, VR = 0, REAL = 0.5.

The main analysis showed no statistically significant difference in cognitive load for any of the dimensions across the three conditions (see Table 6.2). As observed from Figure 6.8, this suggests all the conditions demanded similar effort in processing evaluations across the different dimensions from the participants. Although there were generally no significant effects on each dimension, an emerging trend for the *Visual* dimension can be observed. This trend is seemingly driven by the immersive conditions. Specifically, participants reported lower *Visual* cognitive load as the condition changed from CAE to VR to REAL. However, the standard deviation of the current dataset inhibits acquiring concrete information on the trend.

Table 5.4: Listing the different cognitive load dimensions, indicating how they generally differ across the conditions

Dimension	Estimate	F(1, 91)	t.ratio	p.value
Perceptual	-0.02	0.00	-0.03	0.972
Response	-0.68	1.41	-1.19	0.238
Spatial	-0.52	0.66	-0.81	0.420
Verbal	-0.17	0.06	-0.24	0.809
Visual	-1.09	3.02	-1.74	0.085
Auditory	0.14	0.03	0.18	0.860
Manual	-0.56	0.66	-0.81	0.420
Speech	-0.05	0.00	-0.06	0.949

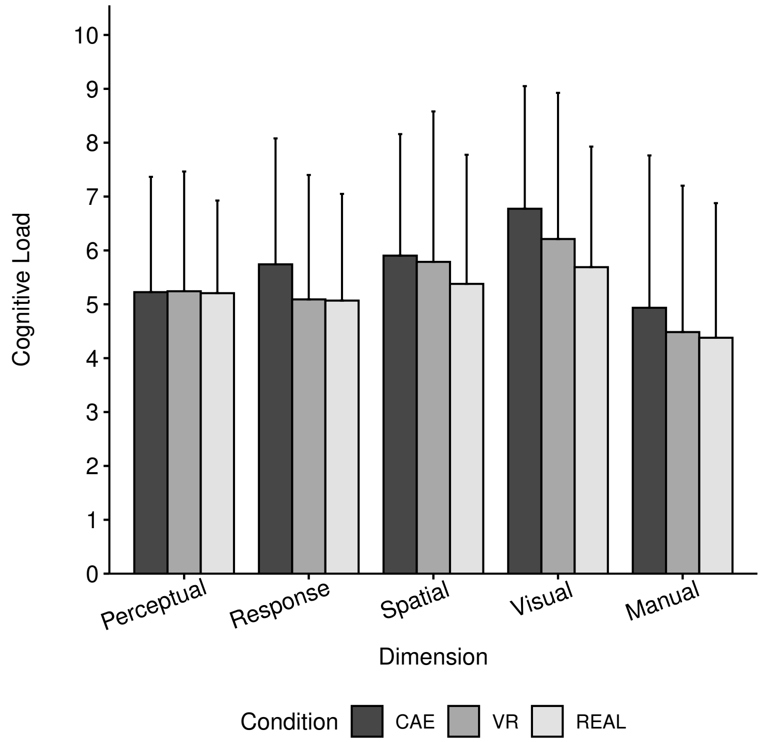


Figure 5.10: Showing the distribution of reported cognitive load as affected by the three conditions

5.4.4. Modality engagement

Results presented in this section are observations of the qualitative method group only. This group conducted the think-aloud task during the DfAM exercise and consisted of only 31 participants. The video and audio recording of each participant's session was coded for the think-aloud task to extract the data. Of the 31 recordings, 6 recordings (two per condition) were randomly selected to establish reliability between the two raters. The remaining 25 recordings were divided between the two raters and coded independently. Reliability between raters was established using the Intraclass Correlation Coefficient (ICC) for average and consistent agreement (see Table 5.5). Any disagreements between the raters were resolved through discussion and consensus.

The data collected from the think-aloud task was analyzed to understand the differences in engagement between the modalities. For this analysis, the engagement was regressed on the centered variable for *Condition* independently for each type of engagement: *Active* and *Passive*. *Condition* served as a between-subjects variable centered around the three studied conditions: CAE = -0.5, VR = 0, REAL = 0.5. Engagement was equated to the number of codes observed per minute of the recording, i.e., the ratio of the total number of codes to the total recording time.

The main analysis showed a significant effect of *Condition* on *Active* engagement, $b = -5.33$, $F(1,73) = 6.65$, $[t(1,73) = -2.58]$, $p = 0.012$, but showed no significant effect on *Passive* engagement, $b = -0.33$, $F(1,73) = 0.03$, $[t(1,73) = -0.17]$, $p = 0.866$. Specifically, participants generally demonstrated higher *Active* engagement in CAE than in VR and REAL, while *Passive* engagement was similar across the conditions (see Figure 5.11). This means that participants generally manipulated the designs more in CAE than in VR and REAL during their DfAM evaluations. Figure 5.11 further shows that the pairwise comparisons of *Active* engagement were significant between CAE and VR, and CAE and REAL, but not between VR and REAL. This means that the differences in *Active* engagement were significant between immersive and non-immersive modalities, but not between the immersive modalities themselves.

Table 5.5: Showing the Intraclass Correlation Coefficient (ICC) between the two raters from coding 6 recordings

PID	Condition	Evaluation	icc.coeff
1	REAL	Active	0.614
1	REAL	Passive	0.658
2	VR	Active	0.880
2	VR	Passive	0.788
3	CAE	Active	0.853
3	CAE	Passive	0.751
4	REAL	Active	0.788
4	REAL	Passive	0.676
5	VR	Active	0.778

Table 5.5: Showing the Intraclass Correlation Coefficient (ICC) between the two raters from coding 6 recordings

PID	Condition	Evaluation	icc.coeff
5	VR	Passive	0.624
6	CAE	Active	0.730
6	CAE	Passive	0.734

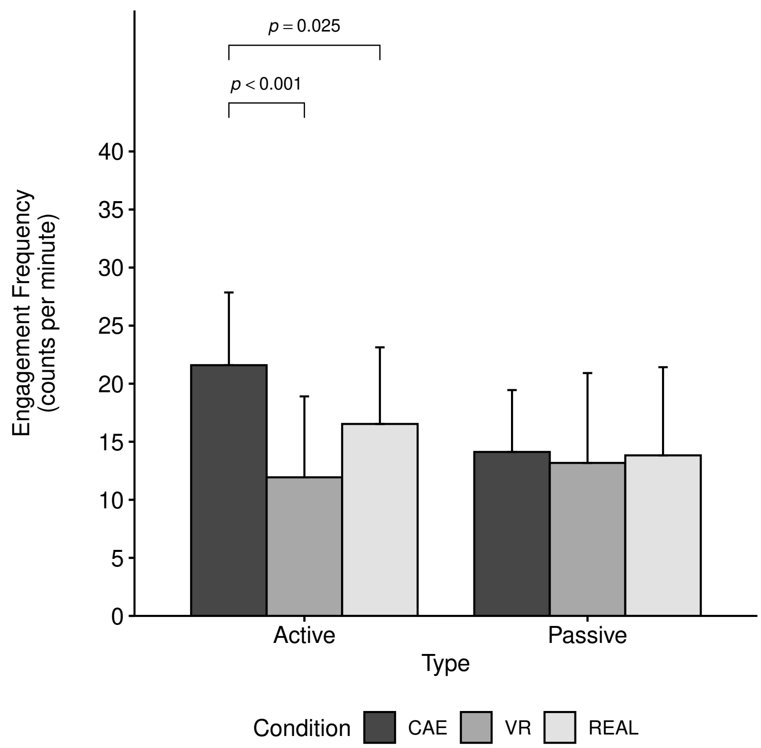


Figure 5.11: Illustrating the observed frequency of engagement for each type across the conditions

5.5. DISCUSSION

Results suggest that outcomes from the DfAM evaluations do not observably vary with the immersion level of the modality. However, the relationship between the immersion level and the outcomes was found to be dependent on the design being evaluated. Additionally, the cognitive load experienced from the evaluations does not vary with immersion; however, emerging trends were observed. Furthermore, the results suggest that a designer's passive engagement with designs does not vary with immersion, but their active engagement does.

The observed findings suggest interesting implications for research in immersive DfAM experiences and the development of digital design experiences with AM. First, these findings demonstrate the potential for immersive VR as a complementary resource to CAE and REAL DfAM decision-making. In other words, designers can transition between CAE, VR, and REAL modalities as preferred without significantly affecting their DfAM outcomes or cognitive load. Such flexibility may also apply to broader DfM workflows that strategically leverage AM with other manufacturing processes. Second, the findings also inform the design of learning modules, indicating the potential for instructors to strategically incorporate VR to intuitively instruct certain DfAM and DfM concepts. As shown in Figure 5.12, VR can be significantly more enjoyable than CAE and REAL for novice users to cultivate DfAM and DfM intuition, with little to no effect on the experiential outcomes. Beyond such broad implications, the remainder of this section breaks down these findings and their implications as they specifically relate to the research questions.

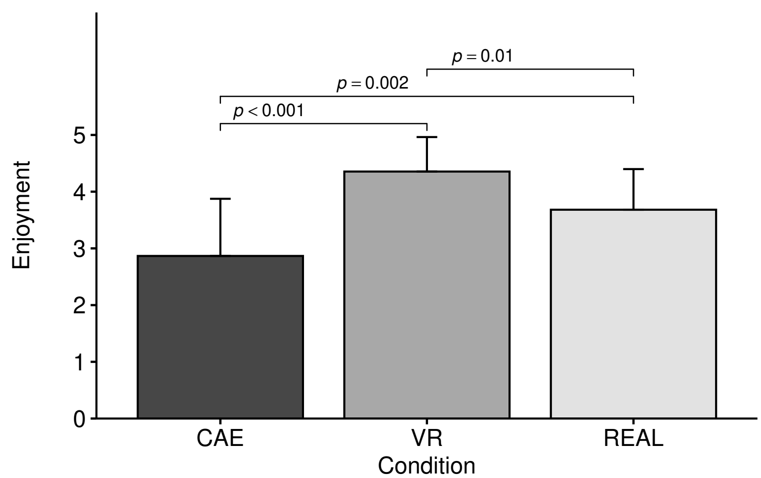


Figure 5.12: Illustrating the reported *enjoyment* experienced from using each modality for DfAM evaluations

How do the differences in immersion between CAE, VR, and REAL modalities affect the outcomes of DfAM evaluations of designs of varying manufacturability?

The goal of RQ 1 was to understand how differences in immersion between modalities affect the outcomes from the DfAM evaluations. It was hypothesized that the VR and REAL evaluations would yield scores closer to expert scores from faster and more confident evaluations, as compared with the CAE evaluations. No significant differences between VR and REAL were expected. Regarding the primary effects of immersion, the results in Section 5.4.2 failed to reject the null hypothesis for each outcome. Specifically, the study could not identify significant differences in DfAM score, evaluation time, and reported confidence between the conditions. The offsets of participant scores from the expert scores were also not significant. In other words, participants consistently under or over-estimated the expert scores by similar amounts across the conditions. It was also hypothesized for RQ 1 that the difference in outcomes between the immersive and non-immersive evaluations would increase for designs with higher perceived complexity. In other words, the effect of immersion on the outcomes was expected to be dependent on the design being evaluated. The results in Section 5.4.2 showed a significant interaction effect between *Condition* and *Design* on the DfAM scores. However, contrary to the hypothesis, the effect of immersion on the DfAM scores decreased as the designs changed from D1 to D6. Specifically, the DfAM scores from the immersive conditions went from being higher than the CAE scores to being lower than them. Comparing these findings to the results in Table 5.3b indicates that participants seemed to lean toward a *neutral* evaluation as the designs changed from D1 to D6.

These are interesting findings because they imply that the modality for evaluating 3D artifacts may not be the driving factor for manufacturability-by-AM evaluations. That is, invoking changes to the mental models of novice designers regarding their application of DfAM may not be driven by digital or physical immersion. Of particular interest here are the observations regarding the REAL condition. Specifically, the implication that physical artifacts may not be necessary for manufacturability-by-AM evaluations, and digital artifacts may suffice. As it stands, participants seem adept at identifying unfavorable and favorable features in the designs but fall short of evaluating them *expertly*. It is worth noting that not identifying such distinctions could have inhibited the study's ability to identify the effects of immersion on DfAM outcomes [99]. Specifically, the lack of diversity in the designs would yield similar scores across the designs, masking any observable differences between the conditions. Therefore, the observed findings may be attributed to either the participants' lack of expertise in AM and DfAM or the nature of the DfAM worksheet used in the study. If the former is valid, a designer's established expertise in AM and DfAM may play a deterministic role in the outcomes. That is, the designers' lack of expertise inhibits their ability to acknowledge "good" designs but not "bad" designs. For the latter, the DfAM worksheet may not be sensitive enough to elicit differences in the designs for those that experts scored highly. However, this may also tie into the designers' lack of expertise in DfAM and their interpretation of the DfAM concepts in the worksheet.

To promote expert-level DfAM reasoning, designers may require digital experiences that critically and comprehensively challenge their mental models of DfAM, beyond what was studied in this research. The added complexity of evaluating assemblies and multi-materials in design workflows may yield results in favor of added immersion [108,110]. Higher task complexity, such as evaluating manufacturability for a variety of print orientations and print parameters, may also identify more significant effects of immersion on DfAM evaluations. This research investigated design evaluation circumstances where such complexities were not present, likely influencing the observed findings or lack thereof. The limited scope may have also limited the observation of nuanced effects of immersion on DfAM outcomes that may be more apparent otherwise.

> *How do the differences in immersion between CAE, VR, and REAL modalities <u>affect the cognitive load</u> experienced when evaluating designs of varying manufacturability?*

The goal of RQ 2 was to understand how differences in immersion between modalities affect the cognitive load experienced from the DfAM evaluations. It was hypothesized that the VR and REAL evaluations would yield a lower cognitive load than the CAE evaluations. No significant differences between VR and REAL were expected. Regarding the primary effects of immersion, the results in Section 5.4.3 failed to reject the null hypothesis for each dimension. Specifically, the study could not identify significant differences in Perceptual, Response, Spatial, Visual, and Manual cognitive load between the conditions. These findings are interesting because this implies that the modality does not influence the effort experienced by designers processing information for DfAM evaluations. In other words, designers may find immersive and non-immersive mediums equally demanding (or comfortable) to evaluate designs for manufacturability by AM. Of particular interest here are the observations with the VR and REAL conditions. Note that participants in VR were generally exposed to a new environment, while those in CAE and REAL worked in familiar environments. Despite this, the results in Section 5.4.3 show that the cognitive load experienced by participants in VR was not significantly different from those in CAE and REAL. With the aid of a brief tutorial phase, this means that the novelty of the VR environment did not adversely influence the cognitive load experienced by the participants. This is interesting because it implies that DfAM evaluations in VR are as cognitively intuitive as those in CAE and REAL, even for novice or first-time users. Regarding the REAL condition, the data further suggests that manufacturability evaluations for AM may not merit the transition from digital to physical artifacts. In the broader scope, this presents interesting implications for how organizations create design workflows for AM.

How do the differences in engagement between CAE, VR, and REAL modalities explain the observed trends in DfAM evaluation outcomes and cognitive load?

The goal of RQ 3 was to understand how differences in immersion between modalities affect engagement with the designs during the DfAM evaluations. It was hypothesized that analyzing how designers engage with the designs will explain the trends observed in RQ 1 and RQ 2. Specifically, by observing how immersion alters the perception of 3D artifacts and other visual information [31,65] and influences the interactions involved. The results in Section 5.4.4, however, present interesting findings that offer key context to the observations in Section 5.4.2 and Section 5.4.3 and their implications. Findings suggest that the modality for DfAM evaluations does not influence the passive engagement with the designs. This means that the designs retained their role as passive artifacts for communication, learning, and decision-making. In other words, designers across the conditions visualized the designs identically to extract information and make decisions. The findings also suggest that the modality strongly influences active engagement with the designs, specifically, when comparing the immersive and non-immersive modalities. Results showed that participants in CAE generally manipulated the designs more than those in VR and REAL. This means that designers in CAE were more likely to interact with the designs to extract information and make decisions.

These findings have strong implications for how a designer's engagement with designs may influence their DfAM evaluation outcomes and cognitive load. The collective findings from Sections 5.4.2 and 5.4.4 imply that high active engagement in non-immersive modalities is required to yield comparable DfAM outcomes to immersive modalities. Active engagement in non-immersive modalities may similarly curb experiencing higher cognitive load than in immersive modalities. These implications suggest immersive DfAM evaluations may not be constrained by the amount of active engagement with the designs, while non-immersive evaluations may be. It should be noted, however, that the comparison between VR and REAL showed an emerging trend (i.e., not a statistically significant trend) for differences in *Active* engagement. That is, participants may manipulate REAL designs more than those in VR, but not as much as those in CAE. A larger sample size could better identify trends between VR and REAL as well; however, it is unlikely to change the overall trend of the findings. Instead, an explanation for this emerging trend in *Active* engagement may be tied to the emerging trend for the effects of *Condition* on *Confidence*. Table 5.3a shows that the confidence reported by the participants seems to decrease as the condition changes from CAE to VR to REAL. A closer inspection of Figure 5.9 shows that participants seemed more confident in their evaluations in CAE and VR than in REAL. This trend suggests that designers may be more confident evaluating digital designs over their physical counterparts. This means that the potentially higher manipulation of the REAL artifacts may be attributed to a lack of confidence in their evaluations.

An explanation for the emerging trend in *Confidence* and its potential relationship to *Active* engagement may be revealed by comparing the VR and REAL think-aloud recordings. First, the recordings showed participants in the REAL condition expressing more uncertainty in their evaluations. Since they were not given any information on the fabrication process and were novices in AM and DfAM, their mental models for manufacturability by AM may have been challenged by witnessing the fabricated artifacts. This phenomenon may have influenced the participants to manipulate the physical artifacts more than expected, perhaps to ascertain the fabrication process, contributing to the higher *Active* engagement in the REAL condition. Second, a further examination of the recordings for participants in the VR condition showed participants moving around the 3D model more than manually manipulating it. Specifically, the authors observed participants picking up the 3D model, manipulating it, and then suspending it in free space. Interestingly, they would then switch between moving around the model and moving the model around, with the former being more frequent than anticipated. While still recorded as *Active* engagements, they were generally observed to be brief, further contributing to the emerging trend for *Active* engagement. This suggests that the participants may have been more comfortable moving around the 3D model in VR than manipulating it. Whereas those in the REAL condition may have been more comfortable manipulating the physical artifacts than moving around them. Controlling for the uncertainty from DfAM evaluations of physical artifacts may present an interesting implication for how designers actively engage with the designs in immersive modalities. Specifically, digital immersion may induce more *non-manipulative* active engagement whereas physical immersion may induce more *manipulative* active engagement with designs.

Of additional interest in the observed findings is the lack of influence of higher active engagement in CAE on cognitive load. It makes sense that designers must frequently manipulate the 3D models to better evaluate them in non-immersive modalities. Given that cognitive load also does not vary with immersion (Section 5.4.3), habitual familiarity with the modality may play a key role in the effort exerted by the designer. That said, Table 6.2 does show an emerging trend for the effect of *Condition* on *Visual* cognitive load. A closer inspection of Figure 6.8 shows a decrease in *Visual* cognitive load progressing linearly by the level of immersion. Specifically, the *Visual* cognitive load reported by the participants decreased as the condition changed from CAE to VR to REAL. Note that *Visual* processing cognitive load requires using attentional resources to process and interpret the meaning of visual information gained through sight. For example, seeing a sign on the road and comprehending what that means is an example where visual processing is used. In the DfAM evaluations, designers visually process a design's features and the information on the DfAM worksheet. This is a prerequisite for decision-making, which would trigger *Perceptual* processing cognitive load. However, the *Perceptual* cognitive load did not vary with immersion as shown in Table 6.2. This could mean that the level of immersion may not affect the decision-making but may affect the processing of visual information to make those decisions.

5.6. CONCLUSION

The presented work studied the design of VR experiences for DfAM applications. The goal was to understand how differences in immersion between modalities affect 1. the outcomes from the DfAM evaluations, 2. the cognitive load experienced from the evaluations, and 3. the engagement with the designs during the evaluations. A mixed-methods study was designed to extract quantitative and qualitative insights from the experiences of designers to inform this understanding. Participants evaluated multiple designs for manufacturability by ME in immersive and non-immersive modalities. Results suggest that outcomes from the DfAM evaluations do not observably vary with the immersion level of the modality. However, the relationship between the immersion level and the outcomes was found to be dependent on the design being evaluated. Additionally, the cognitive load experienced from the evaluations does not vary with immersion; however, emerging trends were observed. Furthermore, the results suggest that a designer's passive engagement with designs does not vary with immersion, but their active engagement does.

These contributions have significant implications for how future designers are trained in DfAM to meet the AM demands in the workforce. Specifically, the findings suggest that immersive and non-immersive mediums can be used to train designers in DfAM without affecting their evaluation outcomes and experienced cognitive load. This work also presents interesting implications for how organizations create design workflows for AM. Specifically, the findings suggest that design for AM processes may not have a strong requirement to transition to physical artifacts. Instead, their digital counterparts may suffice for manufacturability evaluations, regarding AM processes like ME. However, designers may need to actively engage with the designs in digitally non-immersive modalities to achieve similar outcomes as those in digitally immersive modalities.

While these are interesting implications for DfAM applications, these findings must be considered with certain limitations of this work. This research limited its scope toward manufacturability evaluation for ME. Material extrusion is a relatively more accessible and functionally less complex process than processes like powder bed fusion. Therefore, the findings from this work may not be generalizable to other AM processes. Future work must expand on these findings and explore learning and intuition development for multiple AM processes. Doing so will aid industries in improving their digital design processes by empowering their designers with insight into the range of AM solutions. Additionally, the DfAM exercise in this work was limited to only visually evaluating designs for AM in a fixed print orientation. Participants did not have the opportunity to manipulate the designs to explore alternative print orientations. They also did not assess the impact of their decisions on the manufacturability outcomes of the designs, such as print time and support usage. Future work must incorporate a design problem that encourages designers to explore alternative print orientations when evaluating designs for AM. Furthermore, this research limited its scope to designers who were novices in AM and DfAM. Such findings may not be generalizable to veterans in the AM industry. Future work must explore the effects of immersion on designers with varying levels of expertise in AM and DfAM. Insight from such work could inform the design of experiences that are tailored to the expertise and needs of the designer.

Similarly, this work studied designers with little to no experience with VR. The observed findings were documented with designers who were habitually familiar with CAE and REAL modalities. Future work must study the role of modality familiarity on the observed findings, as well as investigate the effects of immersion on designers with similar levels of familiarity across CAE, VR, and REAL modalities. Finally, this research limited the scope of the think-aloud analysis to active and passive engagement. However, the subjective nature of how designers think and reason during DfAM evaluations leaves room to incorporate more sophisticated methods of analysis. Consider the emerging trend for *Active* engagement. Note that the recordings for participants in the REAL condition were cropped to anonymize the participants. This means that the raters had a constrained view of the participants' engagement with the designs. Although *fidgeting* was controlled when coding for *active engagement*, limited visibility limits the accuracy of such control. Future work must incorporate more sophisticated methods of analysis to account for such limitations. This could include analyzing eye-tracking and electroencephalography (EEG) data to further examine the designers' mental models and cognitive processes. Future work must also conduct a broader and deeper assessment of a designer's evaluation and decision-making processes to inform the design of immersive DfAM experiences.

Chapter 6

IMMERSION IN DFAM PROBLEM-SOLVING

6.1. INTRODUCTION

Organizations competing against sustainability, cost, and time-to-market requirements are adopting advanced manufacturing technologies to address their engineering challenges. Additive manufacturing (AM) offers a competitive advantage to these groups and is thus increasingly being used to fabricate end-use parts [9]. However, such organizational adoption of AM needs designers who can specifically produce parts that take advantage of AM while accounting for its limitations [11]. This is because parts designed for AM can incorporate unique geometric and material complexities, distinguishing them from parts created using subtractive and formative manufacturing processes [3,8]. There is a shortage of designers with a thorough understanding of DfAM and AM process concepts to meet the demand for AM [4,5,140,141]. This deficit limits AM adoption within organizations, overcoming which is, therefore, crucial to innovate with AM [12,13]. For this purpose, designers must be equipped with design and process-centric AM knowledge for the range of AM processes and materials. This knowledge is essential to cultivating the skill necessary to produce functional and manufacturable parts while minimizing failures, defects, and functional errors. To acquire this knowledge, designers must experience solving problems with AM by visualizing the fabrication of their designs to hone their design for AM (DfAM) intuition. Therefore, this research introduces a DfAM problem and studies how such visualization affects a designer's design and manufacturing decisions for AM.

Visualizing the form, scale, aesthetics, and ergonomics of a solution is a fundamental step in checking its viability during design processes [28,29]. With designs for AM, the solution's manufacturability is also important, making it crucial to visualize and incorporate manufacturing considerations in DfAM processes. The experience of actively working with 3D printers to fabricate functional parts is necessary to visualize the benefits and limitations of AM technologies [14,34,35,115]. Doing so for the range of AM processes fosters a breadth of technical competency and design intuition for AM, essential to innovating with AM [6–8]. Although processes like material extrusion (ME) are quite accessible, others like powder bed fusion (PBF) are not due to their inherently high cost, safety, and infrastructural requirements [20,143]. This limits the hands-on experiences designers can have with AM systems, thus limiting their opportunity to cultivate problem-solving skills for AM. Even with physical access to AM systems, low manufacturing speeds limit rapid learning and problem-solving with AM [187,188]. There is a need for accessible alternatives that support visualizing and testing designs for AM to rapidly cultivate problem-solving skills for AM. Working with virtualized AM systems offers such alternatives, motivating an investigation into the use of virtual experiences for DfAM problem-solving.

Virtual manufacturing methods, such as computer simulations, data models, and other digitally fabricated resources, help visualize and test products and manufacturing processes before their physical realization [132–134]. Science and engineering have historically leveraged simulations, games, and digital twins using computer-aided technologies (CAx) for this purpose [61,62,144,145]. Past work in virtualized AM also shows potential in demonstrating the 3D printing outcomes of different designs to offer such insight [60,137,138]. Although non-immersive virtual simulations have historically been used during problem-solving as alternatives to physical learning and decision-making [116,117], adding immersion shows the potential for improved learning and communication outcomes, key requirements for effective problem-solving [118–121]. This is because modalities like virtual reality (VR) with enhanced immersion and presence influence 3D perception [65] to improve design and engineering experiences and their experiential outcomes [106,107,110,111,149]. Past work even shows promise in specifically teaching design and process-centric AM concepts using VR [137,138,148]. However, no known work investigates how differences in immersion affect the application of such conceptual knowledge on the outcomes of a DfAM problem-solving experience. To address this gap, this research studies how designers additively manufacture their solution to a design problem in either a CAx or VR environment.

Designers must be equipped with digital experiences to visualize their solutions and rapidly solve design problems with AM. To do so, digitally immersive and non-immersive experiences, offered by VR headsets and flat-screen computers respectively, must be examined within AM contexts. Knowledge of their benefits and limitations will inform the design of digital experiences, tailored to enhance designers' problem-solving abilities with AM. The goal of this research is to, therefore, study the use of immersive VR and non-immersive CAx in AM problem-solving. Problem-solving with AM, however, employs two different types of rationalization: 1. applying DfAM knowledge to generate a solution, and 2. identifying the best approach to manufacture the solution. The latter specifically requires designers to assess the best orientation to additively manufacture their solutions. Therefore, this research first tasks designers with generating a 3D model to solve a DfAM problem. They must then evaluate the solution's manufacturability by determining the best print orientation for it in a CAx or VR environment. The effects of immersion on the change in manufacturability outcomes of the designs and the cognitive load experienced by the designers are studied. Section 6.3 describes the study methodology used to address the research questions in Section 6.2. Findings from the data analysis are then presented in Section 6.4 and discussed with their implications in Section 6.5. Lastly, Section 6.6 summarizes the collective contributions of this research and its limitations for future work.

6.2. RESEARCH QUESTIONS

This research aims to investigate how immersion affects how designers manufacture a design with AM by determining the best orientation for fabrication in a CAx or VR environment. The study also observes how cognitive load varies between the two modalities during the problem-solving experience. These research questions guide this investigation:

Research Question 1. *How do differences in immersion between CAx and VR affect the <u>change in manufacturability outcomes</u> of a solution designed for AM?*

This research question identifies the effects of immersion on the change in manufacturability outcomes when problem-solving with AM. Specifically examined are 1. the time spent identifying the best solution, 2. the time taken for print completion, 3. the support material used for the print, and 4. a manufacturability score for the designs (based on the print time and support material used). Compared to the CAx problem-solving, it is hypothesized that the manufacturability designs in VR will yield higher scores, faster prints, and lower material usage. However, no significant differences between the two modalities are expected for the time spent identifying the best solution. Such trends are hypothesized due to expected enhancements in spatial perception and reasoning within immersive modalities [108–111].

Research Question 2. *How do the differences in immersion between CAx and VR affect the cognitive load experienced from manufacturing of a solution designed for AM?*

This research question identifies the effects of immersion on the cognitive load experienced from designing and manufacturing a 3D model to solve a design problem with AM. Specifically examined is the self-reported cognitive load experienced by the designers. Compared to the CAx experience, it is hypothesized that the VR experience will generally yield lower reported cognitive load values. It is expected that the effort required to perform manufacturability evaluation operations for a design, and thus the cognitive load, changes due to the change in immersion. Specifically, evaluations within modalities that require low effort will yield lower reported cognitive load than those that require high effort [83,84,87,88]. Such variation in effort is expected to arise due to differences in immersion, the perceived complexity of the designs, and the required engagement with the designs.

6.3. METHODOLOGY

Participants completed the steps illustrated in Figure 6.1 on an online Qualtrics survey for the designed study. This includes engaging with the questionnaires, instructions, and the CAx and VR AM environments. No personal or identifiable information was collected from the participants. Completing the survey corresponded to opting in for the study; not doing so was registered as *opting out* of the study. Participant data was deleted accordingly as per the approved Internal Review Board (IRB) protocol. The remainder of this section describes the steps completed by the participants for the designed study as shown in Figure 6.1. Section 6.3.1 describes the pre-study procedure, Section 6.3.2 the design of the virtual AM environment, and

Section 6.3.3 the details of the DfAM problem. Lastly, Section 6.3.4 describes the measurement of cognitive load after the DfAM problem-solving exercise.

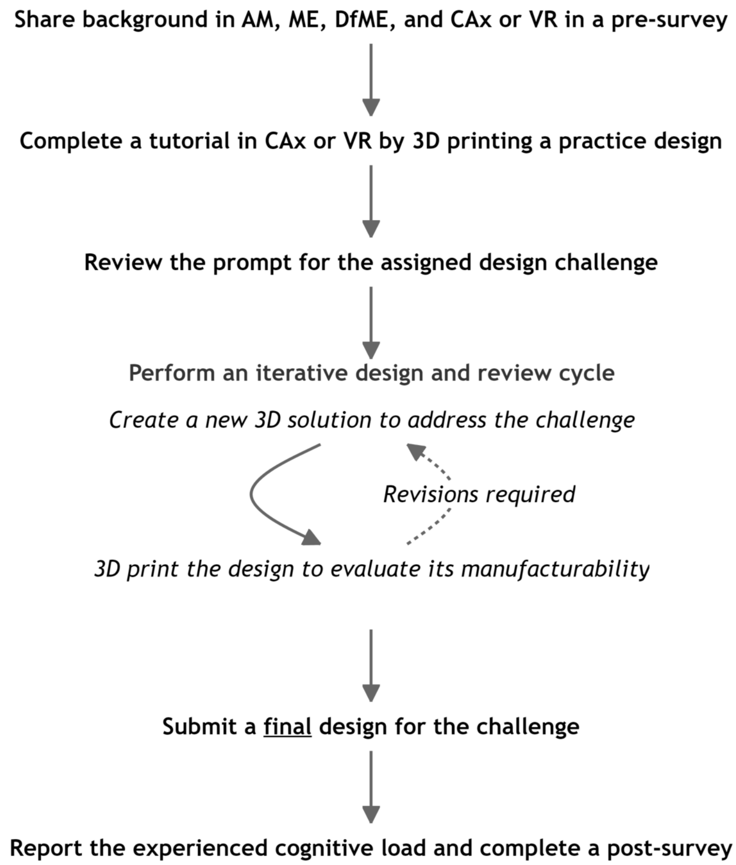


Figure 6.1: Illustrating the order of steps completed by the participants in the CAx and VR conditions for the designed study

6.3.1. Pre-study procedure

Participants in this study were second and third-year undergraduate students from an engineering design methodology course at an R1 university. They were reminded of their rights and options as per IRB protocol before beginning the study. Students who *opted in* were directed to an online Qualtrics survey to begin the study. The survey's hidden algorithm balanced assignments evenly between the two conditions: CAx or VR. Once assigned to a condition, participants first shared their knowledge of AM in the survey. This included their general experiences with AM and their specific experiences with the ME and DfME. This data helped check for prior knowledge in the statistical analysis of the measured outcomes in the study. Knowledge in AM, ME, and DfME was recorded on the following 5-point Likert scale:

1. I have never heard or learned about this topic before this
2. I have some informal knowledge on this topic
3. I have received some formal knowledge on this topic
4. I have received lots of formal knowledge on this topic
5. I am an expert on this topic

Next, participants described their proficiency with their assigned modality, i.e., with CAx and VR. Specifically, they were prompted to share their proficiency in working with or interacting with 3D models. Participants likely had much more experience working with CAx tools than with VR tools. Therefore, it was important to measure, acknowledge, and then balance any differences in technological proficiency before comparing the measured outcomes between CAx and VR. Proficiency in CAx and VR was recorded on this 5-point Likert scale:

1. I have never worked with 3D in this modality before this
2. I am slightly comfortable working with 3D in this modality
3. I am comfortable working with 3D in this modality
4. I am extremely comfortable working with 3D in this modality
5. I am an expert on working with 3D in this modality

Upon completing the questionnaire, participants were informed about their assigned modality for the first time. Those assigned to the CAx condition were directed to the AM environment via a link on their computers. Those in the VR condition were each given a Meta Quest headset and controllers and directed to the AM simulation on the Meta Quest Browser app. Then, participants immediately proceeded to the tutorial: a practice experience designed to familiarize them with their assigned modality and the AM environment described in Section 6.3.2. To familiarize themselves with this new AM environment, participants manufactured one example design during the tutorial. They manufactured the design in various orientations to visualize the outcomes for each orientation. After completing the tutorial, participants were presented with the DfAM problem described in Section 6.3.3.

6.3.2. The virtual AM environment

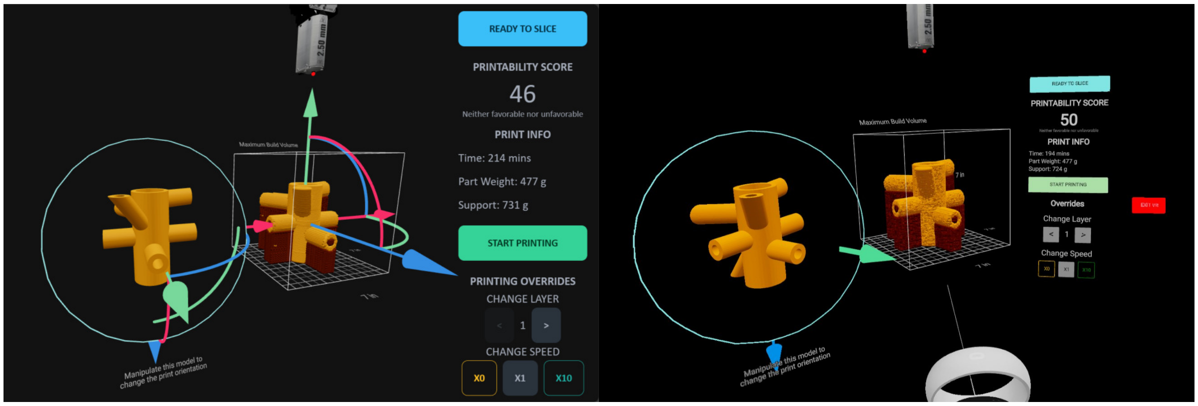
The virtual AM environment used in this research was based on standard 3D printing slicer programs that inform designers about the printing outcomes of their designs. The outcomes in these slicer programs include the time to print completion, the amount of support material used for the print, etc. As such, the virtual AM environment replicated the process of slicing and printing a 3D model for AM to help designers visualize the manufacturability of their designs. The AM environment included four key features to aid designers in visualizing the AM process and assessing the manufacturability of their designs:

1. A 3D model of the solution submitted by the participants
2. A sliced counterpart of the solution in the chosen orientation
3. An extruder to emulate the layer-by-layer printing process
4. A graphical interface to slice models, control the printer, and view the manufacturing outcomes

The designed environments were developed by the authors using openly-accessible software and libraries. The 3D web application was distributed online and accessed by the participants using their web browsers. WebXR technology was used to introduce VR capabilities, and the libraries used to create the 3D environment were the Poimandres react libraries[1] powered by three.js[2]. All the VR experiences were tested on the Meta/Oculus Quest 2 and HTC Vive devices only. The open-source Cura slicing engine was used to slice the 3D models submitted by participants. This slicing was run directly in the browser using a WebAssembly version of the engine[3]. This engine calculated the print outcomes of the designs every time designers submitted a new design or changed the orientation and re-sliced the 3D model. Running the engine behind the scenes allowed the participants to quickly visualize the manufacturability of

[1] Website for react libraries: https://github.com/pmndrs/website
[2] Website for three.js: https://threejs.org/
[3] Source for cura-wasm: https://github.com/cloud-cnc/cura-wasm

their designs in real-time in the 3D environment, similar to standard print slicer programs.



(a) CAx 3D printer (b) VR 3D printer

Figure 6.2: Presenting the design of the AM environments for each condition which included the designed artifact, a 3D printer, and a graphical interface to use the printer and view the print outcomes

To ensure that the DfAM exercise was similar across the conditions, the environments were designed identically as shown in Figure 6.2. Free interaction with a design and its environment was permitted to encourage intuitive exploration of the designs. This means that participants were not restricted to a specific orientation or view of the design and were encouraged to explore the design in multiple orientations. As such, typical engagement included picking up, rotating, and moving the models to get a good view of the design. Scaling or modifying the 3D geometry in the environment was not permitted. This ensured that the designs, and their features, were manufactured at their intended scale, yielding an identical comparison of outcomes between the modalities.

6.3.3. The DfAM problem

Participants were tasked with designing at least one 3D model for a manifold that channels fluid flow from various inlets into a single outlet. No limit was placed on the number of designs that could be created. Participants were also free to use the CAD software they were most comfortable with to design their solution (most used Solidworks). The design problem imposed a *design* and *non-design space*, as visualized in Figure 6.3. The specific design requirements for the manifold were as follows:

- The manifold design must not exceed the 5 x 5 x 5 cubic inch design space
- The wall thickness of each channel must uniformly be at least 0.25 inches
- Each inlet must be directly connected to a channel that leads to the outlet

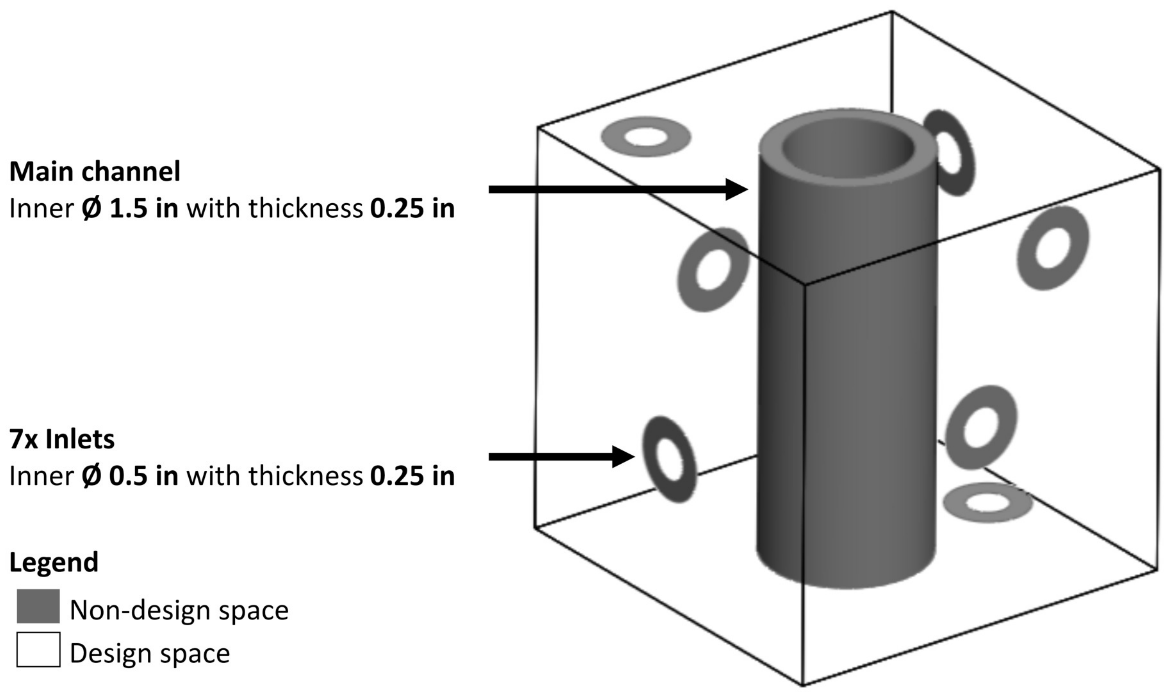


Figure 6.3: Illustrating the *design* and *non-design* space that participants were prompted to consider for the DfAM problem

To simplify and expedite the problem-solving process, a 3D model of the design and non-design space was provided to the participants. This means that participants were not required to create the design and non-design space themselves and could instead focus on designing the channels for AM. This design problem was chosen to reflect the 3D spatial complexity inherent to AM processes and the designs enabled by them. Specifically, the problem forced participants to visualize geometric features in multiple directions and assess their manufacturability for AM. Such spatial complexity also made this a suitable problem to extract the effects of immersion in AM contexts.

Participants were further instructed to consider material extrusion (ME) as the AM process for the design problem. Details about the printer were provided as follows:

- The printer prints with 100% infill (i.e., a solid part)
- It has a 2.5 mm nozzle diameter that deposits material at a 1.875 mm layer height
- The machine has a 7 x 7 x 7 cubic inch build volume

A virtual AM program was provided by the authors to slice and print their solution and determine its manufacturability within these parameters. Participants were required to manufacture each of their solutions using this program to determine their manufacturability before submitting one as their final design. This requirement established a *pre-reviewed* baseline and allowed the comparison to the *post-reviewed* manufacturability outcomes. Specifically, participants were to reason if the default orientation was the best orientation for manufacturing, or if another orientation was better. Changes to the outcomes could, therefore, be attributed to a designer's engagement with the design when fabricating it in their assigned modality.

The design prompt instructed participants to identify a solution that demonstrated favorable manufacturability with AM. To help with this, the AM program displayed the manufacturability score, the time to print completion, the weight of their part, and the amount of support material used for the print. This information was to be used to compare the manufacturability outcomes between the two print orientations. The manufacturability score in particular provided a general assessment of the favorability of the solution for AM. This means that the higher the manufacturability score, the more favorable the solution was for AM. To receive a high score, favorable solutions were expected to:

1. Weigh as little as possible
2. Require little to no wasted support material to fabricate
3. Build in the shortest amount of time possible.

Manufacturability score was calculated using Equation 6.1 where t_{max} and m_{max} were the outcomes from printing a solid cube occupying the entire design space, m_{min} was the mass of a *minimum viable design* for the problem, and t_{min} was the theoretical minimum print time.

$$\text{Score} = 100 \times \left(1 - \frac{t_{norm} + m_{norm}}{2}\right) \tag{6.1}$$

where

$$t_{norm} = \max\left(0,\ \min\left(1, \frac{t - t_{min}}{t_{max} - t_{min}}\right)\right)$$
$$m_{norm} = \max\left(0,\ \min\left(1, \frac{m - m_{min}}{m_{max} - m_{min}}\right)\right)$$

and

$$t_{min} = 0 \text{ mins},\ t_{max} = 239 \text{ mins}$$

$$m_{min} = 300 \text{ g},\ m_{max} = 4974 \text{ g}$$

It is important to note that Equation 6.1 is a normalized cost function. Unlike a normal cost function which is not bounded, this manufacturability score is bounded between 0 and 100. This bounding resembles a grade-like system, serving to make the manufacturability assessment more relatable and intuitive to the participants who were students. Using such a scale for the score aimed to instill internal motivation in the participants, encouraging them to identify the more favorable solutions.

6.3.4. Gauging cognitive load

After manufacturing their designs and identifying the best solution, participants reported their experienced cognitive load from completing the exercise. They used the Workload Profile Assessment (WPA) tool [172] to quantify the cognitive load they experienced. Compared to the Subjective Workload Assessment Technique and the NASA Task Load Index, the WPA's higher sensitivity was preferred for such quantitative assessments [186]. Participants scored eight workload profile dimensions between 0 and 10 to represent their mental exertion. These eight dimensions spanned Perceptual, Response, Spatial, Verbal, Visual, Auditory, Manual, and Speech cognitive processing needs. Participants received a text and audio description of each dimension to review, along with an example of each dimension applied in practice.

Using these descriptions, participants assessed their cognitive load and assigned appropriate values to each dimension, one at a time. The *Verbal* and *Auditory* dimensions, though not directly applicable to the design DfAM exercise, were included to ensure consistency with the WPA tool. This is because the designed experiment did not study any tasks or elements that gave verbal instruction and audio cues. However, the WPA tool was designed to study tasks that would include such elements. The *Speech* dimension was also included under the same rationale. Additionally, this study did not check or correct for any misinterpretations of the dimensions by the participants. Therefore, the inclusion of these dimensions ensured that all the necessary information was collected to study the cognitive load experienced by the participants.

6.4. RESULTS

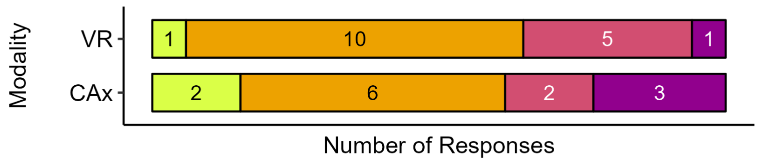
This study measured the effects of immersion on the manufacturability outcomes of an artifact designed for AM and the cognitive load experienced from the DfAM problem-solving experience. Due to the study's opt-in flexibility, participants inconsistently completed the study's elements, resulting in different sample sizes for the different analyses. A total of 40 participants (CAx = 19, VR = 21) generated 3D models for the design problem and manufactured them in either the CAx or VR modality. This sample set serves as the primary pool of relevant data for the study. From this set, 30 participants completed the pre-study questionnaire that recorded their background in AM, ME, DfME, and CAx or VR. Additionally, 25 out of the original 40 reported their cognitive load from the DfAM exercise after completing the design problem. Furthermore, only 14, (CAx = 8, VR = 6) submitted *finished* 3D solutions, that included channels for all the inlets connecting to the outlet as required by the design prompt. This section presents analyses of the background data, the manufacturability outcomes, and the cognitive load data with their respective sample sizes. Specifically, Section 6.4.1 informs on the backgrounds of 30 participants, Section 6.4.2 the manufacturability outcomes of 40 designs, and Section 6.4.3 the cognitive load experienced by 25 participants. Section 6.5 later distinguishes the trends observed with finished and unfinished designs further informing on the underlying phenomenon in the main findings in Section 6.4.2.

To statistically explain the background, cognitive load, and evaluation time data, linear regression models (lm) were generated. Linear mixed-effects regression modeling (lmer) was used to statistically analyze the change in manufacturability score, print time, and support material usage. Pairwise comparisons between variables were done using Estimated Marginal Means tests. The *lmer* utilized restricted maximum likelihood estimation to iteratively modify the parameter estimates with a minimized log-likelihood function. The *lm* and *lmer* model assumptions were checked using the Peña and Slate [173] and the Loy and Hofmann [174] procedures respectively. Unless otherwise specified, this research did not find any observable violations and relies on the acceptable range for the robustness of the respective regression models. A 95% confidence interval was used to determine statistical significance (i.e., $p < 0.05$). The p-values from the *lmers* are adjusted using the Kenward and Rogers adjustment to account for the small sample size. Those from the pairwise comparisons were adjusted using the Bonferroni method to account for multiple comparisons. All potential outliers in the data were retained in each analysis. The reported findings are presented in the following format: $b = 0.00$, $F(n,m) = 0.00$ $[t(n,m) = 0.00]$, $p = 0.00$. Here, b is the regression coefficient (i.e., slope), F is the F-statistic, t is the t-statistic, and p is the p-value. Here n and m are the degrees of freedom in the numerator and denominator respectively.

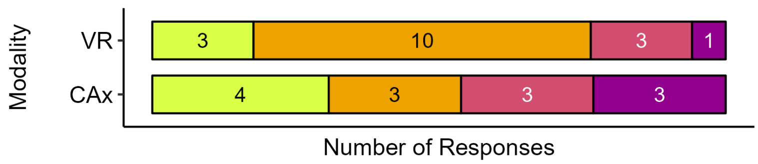
6.4.1. Background analysis

Analyzing the prior knowledge of AM, ME, and DfME concepts from the 30 participants helped account for the effects of such knowledge on the measured manufacturability outcomes and cognitive load. The distributions of the prior knowledge in AM, ME, and DfME were regressed on the centered condition (CAx = -0.5, VR = 0.5) for the analysis. The results showed no observable significant difference between the three conditions in their prior knowledge of

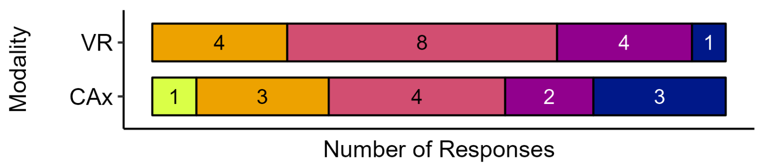
AM, $b = -0.11$, $F(1,28) = 0.12$, $[t(1,28) = -0.34]$, $p = 0.737$, of ME, $b = -0.27$, $F(1,28) = 0.55$, $[t(1,28) = -0.74]$, $p = 0.465$, and of DfME, $b = -0.11$, $F(1,28) = 0.08$, $[t(1,28) = -0.29]$, $p = 0.776$. This trend is observed in Figure 6.4, where participants in all the conditions reported similar prior knowledge of AM, ME, and DfME. Specifically, they shared that they generally had *some informal* or *formal* knowledge of each of the topics.



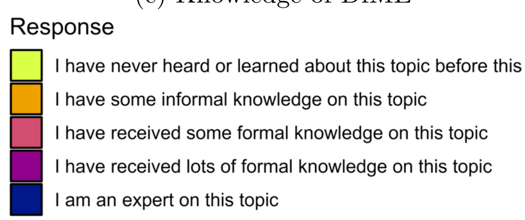
(a) Knowledge of AM



(b) Knowledge of ME



(c) Knowledge of DfME



(d) Common legend for the responses

Figure 6.4: Presenting the distribution of reported prior knowledge of AM, ME, and DfME among the participants in the two conditions

Participants in the CAx and VR conditions also described their proficiency with their respective modalities. Analyzing this data established the need for a tutorial phase for each condition before the main study. The collapsed technology proficiency was regressed on the centered condition (CAx = -0.5, VR = 0.5). As expected, participants generally showed a significantly higher proficiency for CAx technology than for VR technology, *b = -1.72, F(1,28) = 13.68, [t(1,28) = -3.7], p = 0.001.* Specifically, participants in the CAx condition were generally *extremely comfortable* or considered themselves *experts* with CAx technology; however, those in the VR condition had generally *never worked with* VR technology or were *slightly comfortable* with it. This trend shown in Figure 6.5 was expected because students had likely completed CAx/CAD course requirements but likely not any VR coursework. Though expected, the trend echoes the need for a tutorial on VR to balance the technological proficiency between modalities before an AM study (see Section 4.4.1 and Section 5.4.1)

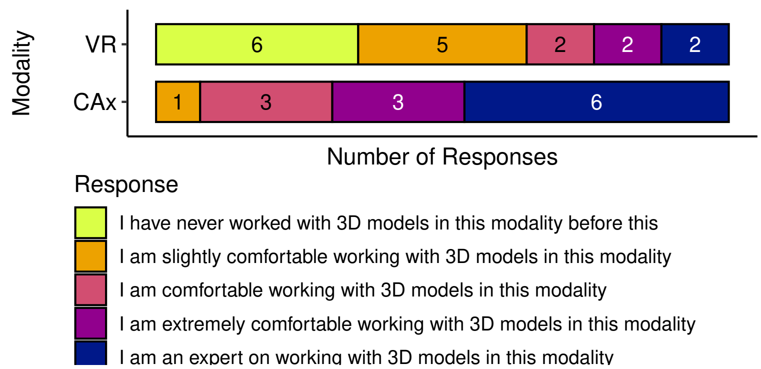


Figure 6.5: Presenting the distribution of reported proficiency on working with CAx and VR modalities

6.4.2. Manufacturability outcomes

The results presented in this section are observations from 40 designs submitted for the study. Analyzing this data helped address the first research question, i.e., identifying the effects of varying levels of immersion on manufacturability outcomes. For this analysis, the manufacturability score, print time, and support material usage were regressed on the centered variables for *Condition*, and *Stage* as a covariate. Evaluation time was regressed on the centered variable for *Condition* only.

Condition served as a between-subjects variable centered around the three studied conditions: CAE = -0.5, VR = 0.5. *Stage* served as a repeated measure for the within-subjects design, centered around the time points in the DfAM exercise: Pre = -0.5, Post = 0.5. The pre and post-stages represent the outcomes observed before and after participants interacted with the design respectively. Comparing the outcomes from the two stages indicates whether participants explored new print orientations for their design besides the one they started with. This comparison sheds light on the influence the CAx and VR modalities had on a participant's engagement to identify a better print orientation for their design. The presented results from the regression analysis focus on each detailed effect when controlling for all other main effects in the model. Only the interaction effects between *Condition* and *Stage* were considered in the analysis. These effects indicate the significance of the *change* in the manufacturability outcomes between the pre and post-stages.

The main analysis showed no significant effect of *Condition* on *Evaluation Time*, $b = -0.91$, $F(1,38) = 0.65$, $[t(1,38) = -0.8]$, $p = 0.426$. Figure 6.6 shows that participants generally spent similar time in the CAx and VR conditions to evaluate their designs.

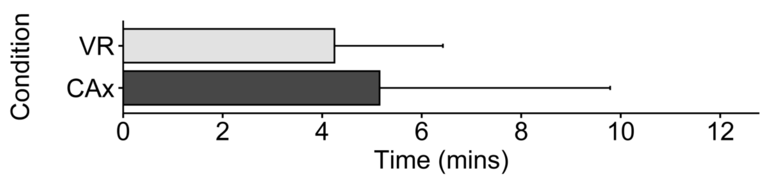


Figure 6.6: Showing the distribution of time spent evaluating one design at a time between the two conditions

The main analysis showed no significant effect of *Condition* on the *Score*, *Print Time*, and *Support Usage* (see Table 6.1). As seen in Figure 6.7, participants generally yielded similar manufacturability scores, print completion times, and support material usage for the designs between the modalities. This means that the manufacturability outcomes were not significantly different in the CAx and VR conditions. However, the analysis did show a significant effect of *Stage* on *Score* and *Print Time* with an emerging trend in *Support Usage*. As also seen in Figure 6.7, participants generally yielded higher manufacturability scores, shorter print completion times, and lower support material usage for their designs at the *Post* stage than at the *Pre* stage. This means that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities.

Estimating a two-way interaction between *Condition* and *Stage* explained how the change in the outcomes differed between the modalities, i.e., the difference in *Score*, *Print Time*, and *Support Usage* between the pre and post-stages. The analysis showed no significant effect from the interaction between *Condition* and *Stage* on *Score*, *Print Time*, and *Support Usage* (see Table 6.1). This means that participants generally made similar changes to the manufacturability outcomes between the modalities. The pairwise comparison of the two stages between each condition further suggested that the *Pre* and *Post* values for each outcome were similar between CAx and VR. However, participants in the VR condition yielded a higher change in *Score* and *Print Time* than those in the CAx condition (see Figures 6.7a and 6.7b). An emerging trend can also be observed in *Support Usage* (see Figure 6.7c). This means that *Condition* may not significantly affect the manufacturability outcomes, but it may strongly influence the *change* in these outcomes.

Table 6.1: Listing the general effects of each variable on the manufacturability outcomes of all the designs

(a) Manufacturability score

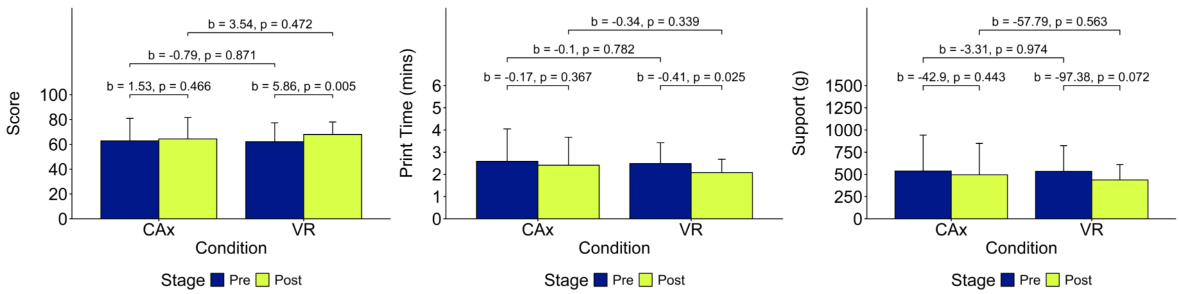
Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	1.37	0.09	0.29	0.770
Stage	3.69	6.67	2.58	0.014
Condition:Stage	4.33	2.29	1.51	0.138

(b) Time to print completion

Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	-0.22	0.44	-0.67	0.509
Stage	-0.29	5.18	-2.28	0.029
Condition:Stage	-0.24	0.91	-0.95	0.347

(c) Support material used

Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	-30.55	0.11	-0.33	0.740
Stage	-70.14	3.37	-1.84	0.074
Condition:Stage	-54.49	0.51	-0.71	0.480



(a) Manufacturability score (b) Time to print completion (c) Support material used

Figure 6.7: Showing changes to the manufacturability outcomes as affected by the two conditions

6.4.3. Cognitive load

Results presented in this section are observations from data provided by 25 participants. Analyzing the data collected from this group helped address the second research question, i.e., identifying the effects of varying levels of immersion on cognitive load. For this analysis, the *Verbal*, *Auditory*, and *Speech* dimensions were excluded (though included in the survey, see Section 6.3.4) and the *remaining* five dimensions were regressed on the centered variable for *Condition*. *Condition* served as a between-subjects variable centered around the three studied conditions: CAx = -0.5, VR = 0.5. The main analysis showed no statistically significant difference in cognitive load for any of the dimensions between the conditions (see Table 6.2 and Figure 6.8). This suggests that determining the manufacturability of one's design in CAx and VR demands similar effort across the different dimensions.

Table 6.2: Listing the different cognitive load dimensions and showing how they differed between the conditions

Dimension	Estimate	F(1, 23)	t.ratio	p.value
Perceptual	-0.20	0.06	-0.25	0.801
Response	0.10	0.02	0.14	0.893
Spatial	-0.53	0.43	-0.65	0.520
Visual	0.23	0.10	0.31	0.759
Manual	-0.33	0.16	-0.40	0.695

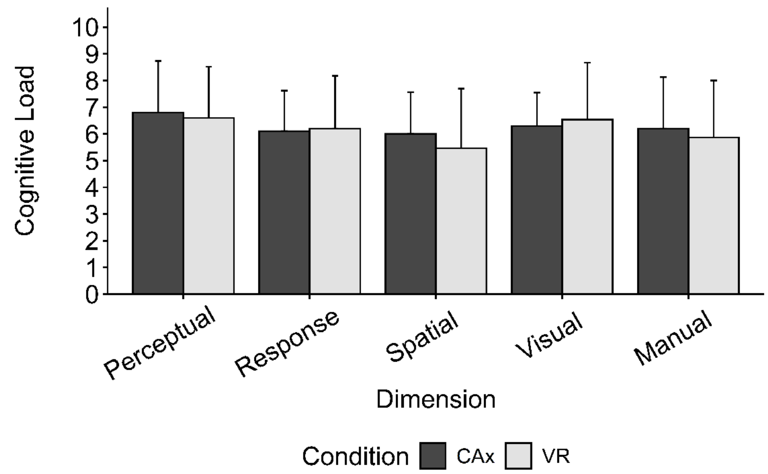


Figure 6.8: Showing the distribution of reported cognitive load as affected by the two conditions

6.5. DISCUSSION

The goal of this study was to observe how varying levels of immersion affect the manufacturability outcomes of an artifact designed to solve a problem with AM. Specifically, participants were tasked with generating a 3D model to solve a design prompt and then manufacturing it with AM in either a CAx or VR environment. To explain the results from Section 6.4 from this study, this section first summarizes the main findings and emphasizes their broader implications. It then discusses emerging trends from a post hoc analysis to discern the underlying phenomenon.

6.5.1. Main findings

This study investigated two research questions to understand the effects of immersion on the manufacturability outcomes and cognitive load experienced from solving a DfAM problem.

> *How do differences in immersion between CAx and VR affect the change in manufacturability outcomes of a solution designed for AM?*

The goal of RQ 1 was to identify the effects of varying levels of immersion on the determined manufacturability outcomes of an artifact designed for AM. The results from Section 6.4.2 showed that the manufacturability outcomes were not significantly different between the CAx and VR conditions. However, the results also showed that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities. This is interesting because it suggests that participants reconsidered their DfAM intuition after visualizing the manufacturability of their designs in new ways. Additionally, the modalities generally did not influence the manufacturability outcomes themselves, but they did influence the change in these outcomes. Specifically, participants in the VR condition yielded a higher change in manufacturability score, print completion time, and support material usage than those in the CAx condition. Because the pre and post-values were similar between the conditions, these trends were likely due to a large difference between the pre and post-means. In other words, the statistical significance was likely due to a high nominal difference between the means and low variation within each condition.

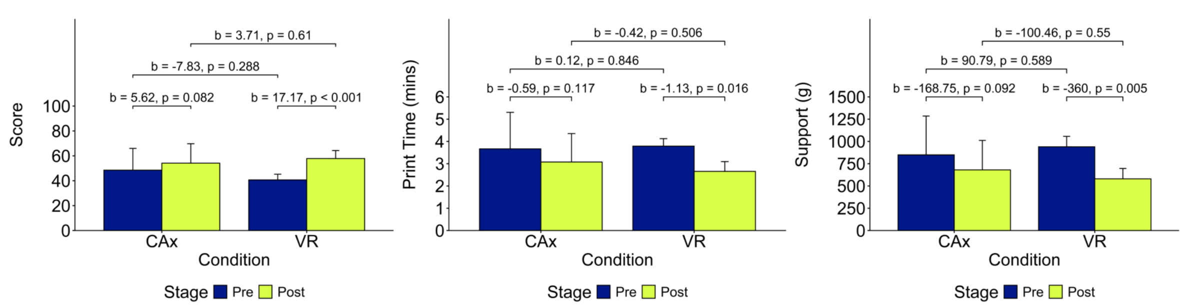
> *How do the differences in immersion between CAx and VR affect the cognitive load experienced from manufacturing of a solution designed for AM?*

The goal of RQ 2 was to identify the effects of varying levels of immersion on the cognitive load experienced from solving a DfAM problem. The results from Section 6.4.3 showed that the cognitive load experienced by participants was not significantly different between the CAx and VR conditions. This means that working in CAx and VR demanded similar mental effort across the different dimensions while determining the manufacturability of one's design. These findings resemble the effects observed on cognitive load from previous investigations of using VR in AM and DfAM contexts (see Section 4.4.3 and Section 5.4.3). Specifically, the results suggest that the added immersion in VR may not significantly change the mental effort required to work with AM and DfAM applications.

6.5.2. Post hoc trends

This study used a design challenge to encourage 3D design thinking that required skill in 3D spatial perception and visualization, a shared characteristic of DfAM and VR. However, the likely lack of motivation or fundamental CAD skills in the participants limited the study's dataset to 14 finished designs. The effects of immersion observed on the manufacturability outcomes of the finished designs must be isolated from those for the unfinished designs. This is because participants who submitted unfinished designs did not apply DfAM considerations for the required functionality specified in the design prompt. In other words, they did not explore connections from all the inlets to the outlet, limiting the challenge to their 3D spatial perception and visualization ability. The degree to which the design was unfinished was irrelevant to this classification. Independent post hoc analyses of the finished and unfinished designs, therefore, discerned the underlying phenomenon in the main findings.

First, analyzing data from only the 14 *finished* designs showed a significant effect of the interaction between *Condition* and *Stage* on *Score*, *Print Time*, and *Support Usage* (see Table 6.3). This means that participants who reviewed finished designs generally yielded a significantly higher change in manufacturability score with the increase in immersion between the modalities. The pairwise comparison of the pre and post-stages shown in Figure 6.9a explained that participants in VR yielded a higher change in *Score* than those in CAx. Figures 6.9b and 6.9c indicate that this general trend was attributed to a significant reduction in *Print Time* and *Support Usage* in VR. Participants in CAx, however, also showed emerging trends for a high change in *Score*, seemingly attributed to a reduction in *Support Usage*. These trends are observed with similar pre and post-values for the manufacturability outcomes between the modalities.



(a) Manufacturability score (b) Time to print completion (c) Support material used

Figure 6.9: Showing changes to the manufacturability outcomes of the finished designs as affected by the two conditions

Table 6.3: Listing the general effects of each variable on the manufacturability outcomes of the finished designs

(a) Manufacturability score

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-2.06	0.09	-0.31	0.765
Stage	11.40	25.36	5.04	0.000
Condition:Stage	11.54	6.50	2.55	0.025

(b) Time to print completion

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-0.15	0.07	-0.27	0.794
Stage	-0.86	10.46	-3.23	0.007
Condition:Stage	-0.54	1.04	-1.02	0.327

(c) Support material used

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-4.83	0.00	-0.03	0.975
Stage	-264.38	14.09	-3.75	0.003
Condition:Stage	-191.25	1.84	-1.36	0.199

Next, analyzing data from only the 26 *unfinished* designs showed no observable significance for the interaction between *Condition* and *Stage* on *Score*, *Print Time*, and *Support Usage* (see Table 6.4). This means that participants who reviewed unfinished designs generally yielded similar changes in manufacturability score with the increase in immersion between the modalities. The pairwise comparisons of the different outcomes suggest that participants yielded nearly identical values for *Score*, *Print Time*, and *Support Usage* between the modalities and the stages (see Figure 6.10). Lastly, participants showed no observable difference in the time they spent manufacturing the *finished* designs, $b = -2.42$, $F(1,12) = 1.1$, $[t(1,12) = -1.05]$, $p = 0.315$ (see Figure 6.11a). This was also the case for the *unfinished* designs as shown in Figure 6.11b, $b = 0.02$, $F(1,24) = 0$, $[t(1,24) = 0.01]$, $p = 0.989$.

Table 6.4: Listing the general effects of each variable on the manufacturability outcomes of the unfinished designs

(a) Manufacturability score

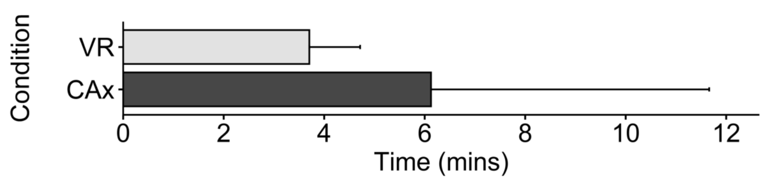
Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	-1.28	0.11	-0.34	0.740
Stage	-0.06	0.00	-0.05	0.962
Condition:Stage	2.79	1.25	1.12	0.275

(b) Time to print completion

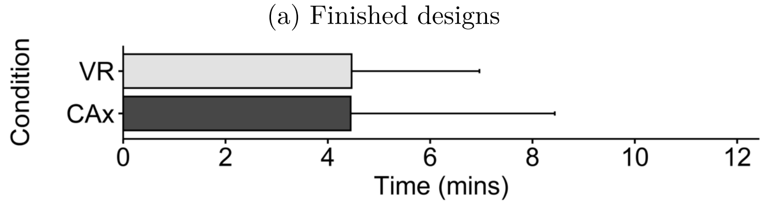
Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	0.04	0.03	0.17	0.864
Stage	0.01	0.02	0.13	0.894
Condition:Stage	-0.26	1.84	-1.36	0.187

(c) Support material used

Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	40.41	0.32	0.56	0.579
Stage	28.15	0.81	0.90	0.378
Condition:Stage	-40.97	0.43	-0.65	0.520



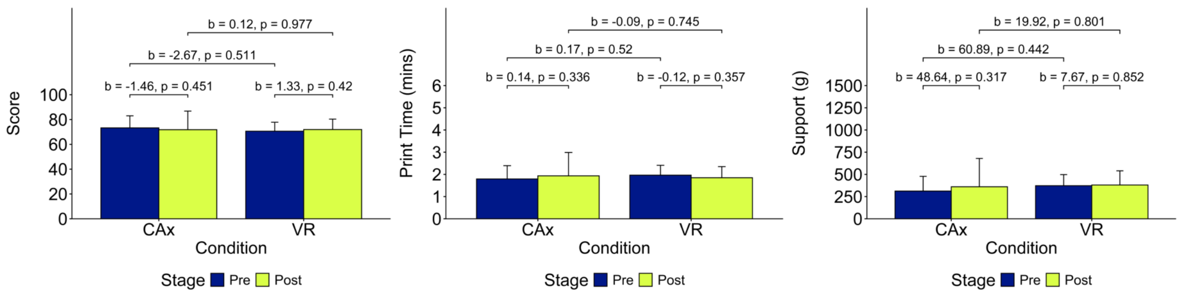
(a) Finished designs



(b) Unfinished designs

Figure 6.11: Showing the distribution of time spent evaluating the finished and unfinished designs between the two conditions

Participants who submitted unfinished designs did not meet the prompted design requirements. As a result, the mixture of finished and unfinished designs in the main analysis obscured the insight extracted from the main findings. Conducting a post hoc analysis of the



(a) Manufacturability score (b) Time to print completion (c) Support material used

Figure 6.10: Showing changes to the manufacturability outcomes of the unfinished designs as affected by the two conditions

finished and unfinished designs isolated the effects observed specific to each. The results of these analyses showed that only the outcomes measured for the finished design represented the intended phenomenon that was measured by this research, yielding more reliable inferences. An interesting inference from this was that participants in the VR condition yielded a significantly higher change in the manufacturability outcomes of their designs than those in the CAx condition. Although this was hypothesized, it is important to note that the sample size for the finished designs was 14 (CAx = 8, VR = 6), which is a small sample size. Further investigation with a larger sample is required to strengthen potential statistical significance.

6.6. CONCLUSION

This research studied the use of VR experiences for DfAM problem-solving. Designers generated original designs for a design problem and additively manufactured them in either a CAx or VR modality to evaluate their design's manufacturability. The goal was to understand how differences in immersion between modalities affect 1. the manufacturability score of the design, 2. the time taken for print completion, 3. the support material used for the print, and 4. the time spent identifying the best solution. Participants evaluated their designs for manufacturability by ME and identified the best print orientation for their designs. Results suggest that experiential outcomes were not significantly different between the CAx and VR conditions. However, the results also showed that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities. Additionally, the modalities generally did not influence the manufacturability outcomes themselves, but they did influence the change in these outcomes. Specifically, participants in the VR condition showed trends in yielding a higher change in manufacturability score, print completion time, and support material usage than those in the CAx condition.

A closer inspection of the observations indicated that the effects observed on the manufacturability outcomes were driven by the effects of immersion on the *finished* designs. This is because the manufacturability outcomes were identical between the conditions and the stages for the unfinished designs. This implies that participants in VR yielded significantly different outcomes to problem-solving with AM when working with fundamentally complex designs. These contributions have significant implications for how future designers are trained in DfAM problem-solving to meet the AM demands in the workforce. Specifically, immersive mediums show the potential to yield a higher change in the manufacturability outcomes of designs for AM. The modality of DfAM problem-solving thus impacts the quality of the end-use parts and the time and material requirements from the fabrication process.

While these are interesting implications, these findings must be considered with certain limitations of this work. This research limited its scope toward manufacturability evaluation for ME. Material extrusion is a relatively more accessible and functionally less complex process than processes like powder bed fusion. Future work must expand on these findings and explore learning and intuition development for multiple AM processes. Doing so will aid industries in improving their digital design processes by empowering their designers with insight into the range of AM solutions. This research also studied designers with beginner and intermediate CAD skills. Future work must account for CAD expertise and study the effects of immersion in problem-solving with AM on designers with varying levels of CAD skills. Additionally, the study did not investigate how problem-solving in immersive versus non-immersive environments changes the design process. Specifically, studying how working in VR and CAx affects changes to the designs generated to solve a design challenge. Future work must observe the iterative design process and document how designers' application of DfAM principles changes with immersion over multiple iterations.

Chapter 7

CONCLUSION

7.1. SUMMARY OF CONTRIBUTIONS

This document shares an investigation into the role of VR experiences in AM and DfAM applications. Presented is evidence of the effects of immersion on AM learning and DfAM problem-solving outcomes from an analysis of designer behavior and experiential outcomes. This includes a new understanding of how immersion affects knowledge gain, cognitive load, and reasoning and decision-making when solving problems with AM. A comparison of how varying levels of immersion affect user experiences further strengthens this insight. Specifically, by identifying how differences in immersion between CAx, VR, and physical environments differ in their effects on AM and DfAM learning and design outcomes. For this purpose, the evidence collected informs on the effects of immersion on 1. knowledge gain, 2. cognitive load, 3. outcomes of DfAM evaluations, and 4. 3D printing designs to solve DfAM problems. This information is consolidated into a framework for designing VR experiences for AM and DfAM applications, a novel contribution to the field of AM and DfAM research.

Before this research, there was a scarcity of knowledge on such effects, with no comprehensive framework guiding such investigations for VR-based AM and DfAM contexts. As such, this research first presents new knowledge on designing VR experiences for AM (see Chapter 3). This knowledge contributes to the lack of literature on design guides for creating immersive experiences specifically for AM contexts. Its key contributions include a generalized framework to inform the design of such experiences and an example VR experience for AM created using the proposed framework. The broader importance of this research is that the proposed framework informs the development of experiences to study and cultivate DfAM intuition, AM process competency, and problem-solving skills.

Next, the research offers new insight into the effects of immersion on AM process learning for different AM processes (see Chapter 4). This insight contributes to the lack of information on how immersive instruction affects interactively learning about AM processes. Findings showed that the differences in immersion and presence between CAI, VR, and in-person instruction do not have a statistically significant effect when learning about ME, but do have a significant effect when learning about PBF. Specifically, VR generally yields equivalent effects in knowledge gain and cognitive load to in-person PBF education while offering advantages in both metrics over CAI learning. The key takeaway from this work is that VR can serve as an alternative to in-person training, opening new possibilities for improving process-centric AM skills of typically high-barrier-to-entry AM processes.

Following this, the research investigated how immersion influences how designers evaluate artifacts on DfAM (see Chapter 5). It contributes new knowledge on the effects of immersion on the outcomes of the DfAM evaluations, the effort required of the evaluators, and their engagement with the designs. Findings indicated that the outcomes from DfAM evaluations in immersive and non-immersive modalities are similar without statistically observable differences in the cognitive load experienced during the evaluations. Active engagement with the designs, however, was observed to be significantly different between immersive and non-immersive modalities. By contrast, passive engagement remained similar across the modalities. The evidence collected has interesting implications for how organizations train designers in DfAM and the role of immersive modalities in design processes. Organizations can provide DfAM resources across different levels of immersion, enabling designers to customize how they acquire DfAM intuition and solve complex engineering problems. The broader impact identified from this research is that the role of VR in DfAM evaluations can be identical to CAx while being more enjoyable and without requiring higher levels of active engagement.

Lastly, the research investigates the effects of immersion on DfAM problem-solving outcomes (see Chapter 6). It contributes new knowledge on the effects of immersion on the 3D printability outcomes of designed artifacts when determining the ideal print orientation. Results showed that manufacturability outcomes are generally not significantly different between the CAx and VR conditions; however, the change in these outcomes is much higher when problem-solving in VR. Specifically, participants in the VR condition showed trends in yielding a higher change in DfAM score, print completion time, and support material usage than those in the CAx condition. Inspecting the differences in outcomes between *finished* designs and *unfinished* designs, participants in VR yielded significantly different outcomes to problem-solving with AM when working with fundamentally complex designs. In other words, the VR condition when compared to the CAx condition yielded a significantly higher increase in DfAM score, and a decrease in print completion time and support material usage. Insight derived from the evidence informs on how future designers must be trained in DfAM problem-solving to meet the AM demands in the workforce. Specifically, key considerations should be made to the potential of immersive environments in yielding a higher change in the manufacturability outcomes of designs fabricated by AM. The broader impact identified from this research is that the role of immersion in DfAM problem-solving thus impacts the quality of the end-use parts and the efficiency of the fabrication process.

7.2. INCORPORATING INTO INSTRUCTIONAL PRACTICE

This research emphasizes the need for immersive instruction of AM and DfAM topics. Specifically, when in-person experiences are inaccessible but spatial presence and interaction foster learning. The findings from this research demonstrate that VR can be a transformative resource to provide active engagement with AM and DfAM concepts in safe and accessible environments. This has important implications for how educators prepare instructional content for AM on learning platforms. To inform the design of such content, this section first describes the process of breaking down AM and DfAM concepts to design modules best suited for immersive instruction. It then describes the process of introducing immersive VR experiences in engineering courses, specifically through learning management systems (LMS) like Canvas, Blackboard, Moodle, etc. Lastly, this section summarizes the logistics of introducing VR content in instructional modules, explaining the key costs associated with the approach.

7.2.1. Choosing the right modality

This research presents a new framework for designing VR experiences for AM (see Chapter 3) and shares an example created using the proposed framework. A key takeaway from this framework that educators must consider is the modularization of learning objectives. Concepts that aim to foster technical skills through task-based learning must be distinguished from those that aim to foster spatial reasoning through problem-based learning. Modules deployed to learning platforms must reflect these distinctions. This is because the scope of the learning objectives will determine the level of immersion best suited for the digital experiences as shown by this research. Specifically, VR experiences may be best suited for active learning objectives where students must interact with the environment and complete tasks to learn about AM concepts. Whereas, non-immersive experiences may suffice for passive learning objectives where students can observe and comprehend the environment to learn. Pairing modules to the right modality is, therefore, a key decision to make when considering the introduction of VR in an instructional module.

Findings from this research inform educators on pairing modules to the right modality when considering the introduction of VR in a course. As demonstrated by this research in Chapter 4, VR mimics in-person education while offering advantages in knowledge gain and cognitive load over CAI learning. This means that educators should similarly utilize VR over CAx for task-based learning modules when in-person experiences are inaccessible. Specifically, when students must acquire procedural knowledge and technical skills by interacting with the environment and completing tasks. As further demonstrated in Chapter 5, design evaluation outcomes, experiential cognitive load, and passive engagement between immersive and non-immersive modalities may be similar. This means that educators are free to choose between VR and CAx for *watch-and-learn* modules where students must observe and comprehend the environment to cultivate spatial reasoning. Specifically, modules where higher active engagement does not correspond to enhanced learning and passive engagement may suffice. Lastly, as demonstrated in Chapter 6, problem-solving outcomes in VR may yield significantly different outcomes to CAx, especially when working with fundamentally complex designs. For such cases, VR may be best suited for problem-based learning modules where students must visualize and actively engage with their environment to solve problems. This is because the learning module likely requires acquiring procedural knowledge and honing spatial reasoning and decision-making skills to solve problems. As such, VR presents a natural environment for students to *learn by doing* and visualize the impact of their decisions.

7.2.2. The costs and logistics of introducing VR content

Virtual reality content must run on dedicated devices, such as VR headsets, to provide the necessary immersive experiences. However, educators may desire to incorporate VR content into eLearning modules through an LMS, making it accessible to students from anywhere. While native VR applications are certainly more performant, they are also more challenging to deploy and update on LMS platforms. They also require high costs in development and maintenance, making it difficult for educators to focus on the content rather than the technology. Web-based VR experiences, on the other hand, run on web browsers, making them more accessible and easier to deploy and update on LMS platforms. However, it is important to ensure that the learning experience is not restricted to VR. In other words, added immersion must be something students can toggle on and off as they please. This means that the same VR experience must also be available in a non-immersive format as demonstrated by this research during DfAM and AM process instruction. For this research, the VR and non-VR experiences were hosted on a separate web server and embedded into the digital surveys used to collect data. A similar approach can be used to host and embed these experiences into an LMS module, within the limitations of the LMS's capabilities. Embedding the experiences can also happen at the instructional design stage. Specifically, through programs like Articulate Storyline and Rise to create interactive eLearning modules before they are SCORM-wrapped and deployed to an LMS.

Although VR content can be intuitively integrated into existing learning platforms, it can be a resource-intensive endeavor. Creating, updating, and maintaining VR experiences requires a learning curve for educators and incurs a financial cost for the equipment and content development. Therefore, the cost of introducing VR content into instructional modules is another key consideration for educators. Introducing VR content requires the use of VR headsets and other hardware with the necessary software to run the experiences. Educators must invest in the development of VR content, which requires expertise in 3D modeling, animation, and programming. Institutions and organizations must carefully consider the investments in this regard, especially when the content is to be developed in-house. This research predominantly used the Meta Quest 2 headset, a standalone VR headset that does not require a computer to operate, priced at $240[1]. The average development time for the VR experiences in this research was 4-5 weeks for 1 developer. For AM and DfAM education, educators may instead consider purchasing 3D printers and materials to provide physical experiences rather than VR headsets and software to provide digital experiences. However, recent work by Totuk et al. advocates for the seamless use of VR and 3D printers in design education [135]. Specifically, it echoes the findings from this research, emphasizing the need to balance the use of in-person, non-immersive, and immersive resources to provide a comprehensive learning experience for AM and DfAM.

Although the cost of introducing VR content into instructional modules is a key consideration for educators, the benefits of VR content are also significant. Purchasing physical resources like 3D printers and materials may be more cost-effective for AM education with processes like ME, but not PBF. Educators must keep in mind the lower costs of VR content compared to in-person experiences, especially when in-person experiences are inaccessible. Additionally, the cost of VR will continue to decrease as the technology becomes advanced. Mixed reality (MR) headsets, for example, are expected to become more affordable too, offering a more seamless switch between physical and digital levels of immersion. The cost of developing VR content will also decrease as the technology becomes more mature, presenting easier tools for educators to create and update VR experiences.

[1]Meta Quest 2, Amazon. Available: https://amzn.com/dp/B099VMT8VZ, Accessed: March 15, 2024

7.3. INTELLECTUAL MERIT

The goal of this research was to provide a comprehensive understanding of the role of VR experiences in AM and DfAM applications. Such an understanding was lacking in the literature, yet is crucial for AM workforce development. First, the literature on the design of active and hands-on experiences was limited to the context of in-person and digitally non-immersive AM instruction. Knowledge of how digital immersion must be incorporated into AM and DfAM experiences was lacking. This research addressed this gap by consolidating literature on learning behaviors, cognitive load theory, and AM concepts to propose a framework for the instructional design of immersive experiences for DfAM and AM process training.

With this framework in place, the research then investigated the effects of immersion on AM process learning. Before this research, the literature was broadly divided into guidance on in-person and non-immersive AM process education and guidance on the use of VR for design and manufacturing education. Published findings from this research help bridge the two domains, providing a new field of study on the effects of immersion on AM process learning.

Knowledge of this field is further expanded upon by incorporating the effects of immersion on DfAM evaluations and problem-solving outcomes. The literature on resources to help hone DfAM intuition was also limited to physical or digitally non-immersive modalities. Additionally, no known work examined how designers engage with artifacts designed for AM within modalities of varying immersion. This research addressed these gaps by providing evidence on the effects of immersion on DfAM evaluations.

Lastly, the literature lacked guidance on how designers solve AM problems by immersively visualizing the impact of their design decisions on the manufacturability of their designs. Specifically, studying the effects of immersion on the 3D printability of a designed artifact when observing how it prints in the selected orientation. Such simulation-driven problem-solving was not previously studied in the context of DfAM within immersive environments. This research addressed this gap by providing evidence on the effects of immersion on how designers create and evaluate solutions for manufacturability with AM. Knowledge gained from all these investigations adds to the existing AM literature, producing new avenues into the study of immersive environments for the design and evaluation of AM artifacts and AM process learning.

7.4. BROADER IMPACT

The intellectual contributions of this research have the potential to transform how designers are prepared for the AM workforce. Cultivating a skilled workforce traditionally utilized in-person and non-immersive resources to learn about AM processes and DfAM concepts. However, with the advent of immersive technologies like VR, training designers with hands-on experiences is now possible without the need for physical resources. This research demonstrates this potential by providing evidence on the effects of immersion on AM and DfAM learning, evaluations, and problem-solving. The significance of the presented findings is that it opens up new and perhaps more effective ways to train designers in AM and DfAM. Instructing designers on processes like PBF in VR was shown to yield similar knowledge gain and cognitive load to REAL instruction but improved outcomes over CAI. When evaluating designs for DfAM, VR was shown to yield similar outcomes to CAE and REAL but with lower active engagement. Combining the learnings from these two investigations into a problem-solving context, VR was shown to yield significantly different outcomes to CAx, especially when working with fundamentally complex designs. Specifically, the VR condition yielded a significantly higher increase in DfAM score, and a decrease in print completion time and support material usage. Connecting the findings from these investigations suggests that there exists a relationship between process-centric considerations and the influence of immersion. Additionally, higher active engagement with the designs may not correlate with better outcomes from DfAM and 3D printing processes. Furthermore, the interdependence between DfAM and AM process factors may play a key role in how designers benefit from immersive experiences.

The broader impact of this research is that VR demonstrates the potential to be a transformative tool for training designers on AM and solving problems with AM. Global engineering challenges have forced industries to seek innovative solutions that are sustainable, low-cost, and quick to market. This means that the evidence from this research suggests that increasing the immersion of AM and DfAM experiences generates a more skilled workforce that can save time, material, and cost in the design and fabrication of parts. This is especially important for industries where weight, cost, and time are critical factors, such as aerospace, automotive, and medical. Equipping designers with immersive resources can enable them to make better decisions regarding manufacturability, improving design processes and the quality of the end-use solutions. Additionally, the observed improvements in technical skills, design evaluation exercises, and problem-solving outcomes make VR a versatile resource for AM workforce development. Organizations must consider investing in immersive VR training to empower their students with the design and process-centric AM knowledge they need to solve problems with AM. Curricula and training programs at institutions may need to be updated to include immersive modules tailored to instruct hands-on concepts on AM. Design and education researchers must also challenge the use of non-immersive resources and study the potential of immersive resources in their experimental design and educational research. Overall, the findings from this research demonstrate the potential of VR to play a transformative role in how designers are prepared to solve engineering problems with AM.

7.5. FUTURE OPPORTUNITIES

This research explored the role of VR experiences in AM and DfAM applications, specifically in AM process learning, DfAM evaluations, and problem-solving outcomes. While the initiative dived deep into key areas of AM workforce development, there remain several opportunities for future work to build upon the findings from this research.

The main limitation of this research was that it did not assess the fidelity and validity of the designed VR experiences for the studied AM and DfAM applications. Although the primary goal of this research was to establish a new domain of knowledge previously lacking in the literature, the VR experiences were not thoroughly evaluated for their studied applications. Specifically, the designed VR experiences were not assessed for their levels of presence or immersion. As such, they were not empirically distinguished from the CAx and physical environments regarding the immersion studied in this research. They were also not assessed on the accuracy of representing the real tasks performed in the environments. In other words, the degree of realism designed was not evaluated, limiting the knowledge of how much the experiences elicit realistic motor movements based on the perceptual and cognitive features of the tasks. Future work should investigate the fidelity and validity of the designed VR experiences for AM and DfAM applications. Established scales to measure presence, immersion, and realism [189] and frameworks to assess the validity of VR experiences [190] must be used to evaluate the effectiveness of VR experiences in transferring knowledge and skills [191]. This will improve the rigor of the research and provide a more comprehensive understanding of the underlying mechanisms influencing the outcomes of AM experiences in VR.

The entirety of this research also only accounted for identical levels of AM, DfAM, and VR knowledge across the participants. This was done to ensure that the observed effects were due to the differences in immersion and not due to differences in prior knowledge. However, the resolution of assessing the participants' prior knowledge was limited, leaving unanswered questions about the role of prior knowledge in the observed effects. Future work should investigate the combined effects of immersion and prior AM/DfAM and CAx/VR knowledge on the observed outcomes. In other words, future work should study how the observed effects change for participants with different levels of expertise in AM, DfAM, and VR. This requires finer granularity in the recruitment of participants, ensuring that the participants are stratified based on their expertise in AM, DfAM, and VR. In addition to segmenting participants, their comfort with and orientation toward VR needs to be validated. This is to ensure that it is indeed comfort that is measured and analyzed and not other factors that could influence the experience. Collectively, such research will inform the design of experiences that are tailored to the expertise and needs of the designer.

Furthermore, the presented research did not thoroughly investigate the change in the design generation process when working with AM in immersive environments. That is, the research did not study how working in VR and CAx affects changes to the designs generated to solve a design challenge. Although participants in Chapter 6 created solutions for a DfAM problem, the research did not track the changes in the designs that were generated to solve the problem. Future work must observe the iterative design process and document how designers' application of DfAM principles changes with immersion throughout multiple iterations in the design process. This insight is crucial to understanding the impact of immersion on the DfAM processes and will refine the role of VR in AM. Adding to such a scope of work, future research must investigate the role of VR in early-stage design ideation and concept generation for AM. Unlike this research, which involved design generation outside of VR, this new scope entails comparing sketching and 3D model generation in VR and CAx. Measuring how concepts incorporate DfAM will demonstrate how designers approach early-stage design in modalities of varying immersion.

Lastly, the scope of this research was limited to assessing short-term effects on knowledge gain, cognitive load, and problem-solving outcomes. This means that how designers carry forward the knowledge and skills they gain from immersive experiences into their design practice was not studied. Future work must explore the long-term effects of immersion on AM learning and DfAM problem-solving outcomes. Specifically, focusing on the retention and transference of knowledge from VR-based AM experiences to other situations is crucial to understanding the broader impact of immersive VR on AM workforce development. Such an investigation will have significant implications for the design of curricula and training programs for AM and DfAM education. Additionally, the presented research only measured the cognitive load that was experienced after each of the different learning and problem-solving interventions. No baseline was established prior to the interventions, leaving room for future work to investigate the change in cognitive load after solving problems with AM in immersive environments. Such an investigation can add to AM literature by identifying the factors that contribute to the change in cognitive load during AM process learning and DfAM problem-solving.

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VITA

Before doing his Ph.D. in Mechanical Engineering from The Pennsylvania State University, Jayant Mathur received his Master's in Engineering Design from Penn State in 2021 and a Bachelor's in Mechanical Engineering from the University of California, San Diego in 2017. For his doctoral program, his research focuses on design for additive manufacturing and experiences in virtual and augmented reality. He has published several peer-reviewed papers on these topics and has presented at numerous conferences, pioneering the knowledge behind using virtual reality for additive manufacturing applications.

Jayant also has extensive experience in both industry and research, applying his skills in additive manufacturing, virtual and augmented reality, and engineering design. As a Digital and Immersive Training Intern at GTI Energy in 2023, he developed innovative virtual reality and augmented reality modules and analyzed training feedback. His internship at Steelcase in 2020 involved developing safe workspace solutions and optimizing design processes. With experience as an Additive Manufacturing Engineer at XponentialWorks between 2017-2019, Jayant coordinated product design and managed 3D printer operations. Concurrently, through his role as a Research Assistant at Penn State's Made by Design Lab since 2019, Jayant has diversified his expertise and engineered solutions such as a machine learning-backed mobile user interface evaluation pipeline.

Additionally, Jayant has consulted for companies as a Virtual Reality and Design for Additive Manufacturing Expert for 3dpmaven in 2023, advising their clients on implementing virtual reality and addressing challenges in 3D printing. He has also participated in industry panels, serving as a panelist at the 2022 ABC Tech Expo discussing applications of additive manufacturing and virtual reality in construction. Jayant lent his expertise further as an Expert Committee Member for the 2023 3D Printing Industry Awards. He has also contributed his knowledge through committee service, as a member of Penn State's Department Head Search Committee in 2021. Furthermore, Jayant has held teaching roles, currently serving as a Teaching Assistant at Penn State instructing on design for additive manufacturing.