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Fresh in My Mind! Investigating the effects of the order of presenting opportunistic and restrictive design for additive manufacturing content on students' creativity

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ABSTRACT

To capitalise the design freedoms enabled by additive manufacturing (AM), designers must employ opportunistic and restrictive design for AM (O- and R-DfAM respectively). The order of information presentation influences the retrieval of said information; however, there is a need to explore this effect within DfAM. We compared four variations in DfAM education: (1) O-DfAM followed by R-DfAM, (2) R-DfAM followed by O-DfAM, (3) only O-DfAM, and (4) only R-DfAM by evaluating: (1) students' DfAM self-efficacy, (2) their self-reported DfAM use, and (3) design creativity. All students trained in DfAM demonstrated an increase in R-DfAM self-efficacy; however, only students trained in O-DfAM, with or without R-DfAM, reported an increase in O-DfAM self-efficacy. Furthermore, students trained in R-DfAM first followed by O-DfAM generated more creative ideas.

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1. Introduction

Engineering design can be broadly described as the process of problem-solving by employing knowledge from different domains. Of the various domains of knowledge utilised in engineering design, the knowledge of manufacturing processes plays a crucial role as manufacturing processes govern the extent to which designers' solutions are economically viable and feasibly made. Designers are encouraged to integrate design for manufacturing and assembly (DfMA) (Boothroyd 1994) in engineering design to account for the characteristics of traditional manufacturing processes early in the design process with the objective of reducing manufacturing cost and time. For example, Selvaraj, Radhakrishnan, and Adithan (2009) demonstrate that by incorporating DfMA concepts such as standardised geometries, engineering designers can reduce manufacturing time and costs when using sheet metal process.

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At the basic level, DfMA guidelines have historically been restrictive, i.e. they primarily focus on the limitations of the associated manufacturing and assembly processes. For example, DfMA guidelines recommend simplifying parts for ease of manufacturing or reducing the number of parts in an assembly (Poli 2001; Pahl et al. 2007). Novel additive manufacturing (AM) processes – in addition to exhibiting several characteristic limitations – provide designers with unique manufacturing capabilities that are enabled by AM's layer-by-layer fabrication process (Campbell, Bourell, and Gibson 2012). The adoption of AM processes in several industries (see (Smith 2013; Renishaw Inc. 2017; Donaldson 2019) for examples) has encouraged a transition from traditional limitation-based DfMA processes towards a dual design for AM (DfAM) mindset (Vayre, Vignat, and Villeneuve 2012).

A dual DfAM approach helps designers leverage AM capabilities – through opportunistic DfAM – while accommodating AM's limitations – through restrictive DfAM (Laverne et al. 2015). Some examples of restrictive DfAM include: (1) the need for support structures (Strano et al. 2013; Das et al. 2015; Hu, Jin, and Wang 2015), (2) warping of parts due to thermal stresses (Li et al. 2015; Zhu et al. 2016), (3) anisotropy and weakness in build direction (Ahn et al. 2002; Bellini and Güçeri 2003; Carroll, Palmer, and Beese 2015), (4) surface roughness due to stair-stepping (Nuñez et al. 2015; Boschetto and Bottini 2016; Delfs, Toows, and Schmid 2016), and (5) limited feature size and accuracy (Fahad and Hopkinson 2012; Moylan et al. 2012; Lockett et al. 2017; Umaras and Tsuzuki 2017). These restrictive DfAM techniques help improve the producibility of AM designs and thereby minimise losses due to build failures (Booth et al. 2017). In contrast, opportunistic DfAM techniques help designers leverage the unique capabilities of AM. These capabilities include the ability to: (1) mass customise parts (Tuck et al. 2008; Pallari, Dalgarno, and Woodburn 2010; Lei et al. 2016; Mohammed, Fitzpatrick, and Gibson 2017), (2) consolidate parts and build assemblies to reduce assembly costs (Calì et al. 2012; Schmelzle et al. 2015), (3) build complex geometries (Rosen 2007; Chu, Graf, and Rosen 2008; Murr et al. 2010), (4) embed external components to improve design functionality (Lopes et al. 2012; Wicker and MacDonald 2012; Aguilera et al. 2013), and (5) print with multiple materials (Doubrovski et al. 2015; Garland and Fadel 2015; Meisel and Williams 2015). These AM capabilities open up designers' solution space – both geometric and functional – beyond the capabilities of traditional manufacturing (Gibson, Rosen, and Stucker 2015). Therefore, opportunistic DfAM helps designers capitalise on the capabilities of AM processes in addition to ensuring the viability and feasibility of designs through the integration of restrictive DfAM (Seepersad, Allison, and Sharpe 2017; Simpson, Williams, and Hripko 2017).

By exposing designers to new design freedoms, opportunistic DfAM enables designers to be creative in their designs; however, prior work has demonstrated that despite being trained in opportunistic DfAM, designers tend to simplify their designs (Pradel et al. 2018a; Prabhu et al. 2020b) possibly under the long-lived assumption that simpler designs are easier to manufacture (Poli 2001; Pahl et al. 2007). Moreover, this outcome could also be attributed to the ease with which simpler conceptual designs can be translated into higher fidelity representations such as CAD, especially by novice designers with low levels of prior experience in CAD. This presents the need for engineering design education to encourage designers to transition from a limitation-based DfMA mindset towards adopting a dual design mindset.

Furthermore, to successfully encourage the creative application of DfAM, design educators must not only encourage successful learning, but also the retrieval and application of DfAM knowledge – both opportunistic and restrictive – during appropriate stages of the design process. Several researchers (see Section 2.2) have demonstrated that the order of presentation of information as well as the nature of the content influences individuals' learning of information. Therefore, the order of presenting opportunistic and restrictive DfAM could influence designers' learning and retrieval of both these domains of DfAM. While several studies (reviewed in Section 2.3) have discussed effective techniques for integrating DfAM in engineering design and design education, few have explored how the order of presenting the dualistic nature of DfAM affects students' learning and use of DfAM. Our aim in this research is to explore this gap in the literature through an experimental study. By exploring this research gap, we aim to inform the formulation of DfAM educational interventions that effectively increase students' learning and retrieval of DfAM concepts in DfAM tasks. Furthermore, we aim to inform the formulation of educational interventions that encourage students to generate creative solutions – i.e. solutions that (1) are novel or unique, (2) effectively solve the problem, and (3) utilise DfAM concepts – in DfAM tasks.

In the next section, we discuss prior research that informed this study; the resulting research questions and our corresponding hypotheses are presented in Section 3. Our experimental method is discussed in detail in Section 4, the results of the experiment are discussed in Section 5, and the educational implications of these results are discussed in Section 6. Finally, the paper concludes with a discussion of limitations and potential directions for future research in Section 7.

2. Review of related work

The work presented in this paper was motivated and informed by prior work related to (i) the role of domain knowledge in creativity, (ii) the effect of order in learning, and (iii) previous DfAM interventions. We present a summary review of the literature in these three areas next.

2.1. Domain knowledge in creativity and problem solving

The capabilities of AM processes provide designers with new freedoms, thus enabling them with the ability to solve problems with more creative designs. To fully leverage these design freedoms, designers must not only be aware of the characteristics of AM processes but also integrate this domain knowledge into their design and problem-solving processes.

Several researchers have proposed models that highlight the role of domain knowledge at various stages of problem solving and creativity. For instance, Amabile's (1996) Componential Model of Creativity proposes one's creative process to comprise the cognitive components of (1) task motivation, (2) domain knowledge and skills, and (3) creativity processes. These cognitive processes drive the creative process through multiple iterations of problem identification, information gathering and preparation, response generation, and response evaluation until a successful or satisfying outcome is attained. Of these various stages of creative problem solving, domain skills inform two key stages: (i) information gathering to initiate response generation, and (ii) response validation and evaluation.

Similarly, researchers in entrepreneurship argue for the importance of information in the discovery of new ideas (Jensen and Heckling 1995; Hayek 2009), with constrained, systematic idea searches demonstrating greater success (Fiet and Patel 2008). Gielnik et al.

(2012) further suggest that the relationship between one's divergent thinking skills and one's ability to come up with new business ideas is influenced by the diversity of information possessed by the individual. Their work found that individuals with a more diverse set of information had a strong positive correlation between divergent thinking and idea generation. In contrast to these findings, Wiley (1998) argues that experts characterised by greater domain knowledge are often less accurate, demonstrate solution fixation, and are slower when compared to non-experts. These effects are further augmented when higher domain knowledge leads experts towards misleading information.

These studies demonstrate that for domain knowledge to successfully influence creativity, designers must not only effectively *learn* the information, but also *retrieve* the appropriate information in the preparation and response validation stages. Therefore, for the successful application of DfAM, designers must learn and then retrieve both opportunistic and restrictive DfAM during the various stages in the design process, especially concept generation. This retrieval of domain knowledge has been shown to be influenced by the order in which information is learned and individuals' familiarity with the information as summarised next.

2.2. Role of order in learning (and forgetting)

For an educational intervention to successfully encourage creativity, domain knowledge must not only be effectively learned but also retrieved at the appropriate stage(s) during the design process. Successful retrieval is influenced by forgetting (Ebbinghaus 1913), which could be caused by both the lack of access to the information (Tulving and Pearlstone 1966) and the unavailability of the information itself (Tversky and Kahneman 1973). Forgetting of information can be attributed to several causes such as interference (McGeoch 1932; Underwood 1957; Mensink and Raaijmakers 1988; Anderson and Neely 1996), decay with the passage of time (Thorndike 1913), and context shifts (Pan 1926; Mensink and Raaijmakers 1988), each of which interacts with each other to result in forgetting (McGeoch 1932; Anderson 2009). Of these factors, interference is strongly influenced by the order in which information is presented (Barnes and Underwood 1959). Interference-induced forgetting occurs when the recall of certain information is impaired by the storage and recall of similar, competing information (Anderson and Neely 1996), and it is attributed to the stronger recall association of competitor information to certain cues (Anderson, Bjork, and Bjork 1994). Moreover, researchers argue that this inhibition is caused by an overload of information associated with the same retrieval cue (Watkins and Watkins 1975) and this can occur along two paths: (1) retroactive inhibition and (2) proactive inhibition. Retroactive inhibition occurs when the retrieval of old information is hindered due to memory inhibition caused by the learning of new, similar information (Britt 1935). In contrast, proactive interference is the impaired retrieval of new information due to the stronger cue association of old information (Whitely 1927).

The similarity between the old and new information plays a crucial role in recall inhibition. Researchers have argued that retroactive inhibition in the recall of new information is influenced by the similarity (Robinson 1920; McGeoch and McDonald 1931) and semantic-relatedness (Blaxton and Neely 1983) between the old and new information. Robinson (1927) and Harden (1929) argue that a higher similarity between the original and new information results in better recall of the original information. However, Young (1955) demonstrates that while retroactive inhibition is influenced by the similarity between the old and new information, this effect was not seen in case of proactive inhibition. In the context of DfAM learning, the similarity between restrictive DfAM and limitation-based traditional DfMA – the current standard for design for manufacturing education – could inhibit students learning of novel, opportunistic DfAM concepts.

In addition to the similarity of information, recall inhibition is also influenced by one's familiarity with the information, and this varies based on the method of learning (McGeoch 1929). For example, studies by Robinson and Heron (1922) and Robinson and Darrow (1924) demonstrate that a greater degree of learning of the original information – as assessed by the amount of material – corresponds to a lower retroactive inhibition. Similarly, Brown (1968) and Karchmer and Winograd (1971) demonstrate that in free recall situations, a stronger familiarity with information results in an impaired recall of information with weaker associations. A similar argument is made by Underwood (1949) who argues for the effect of degree of learning on proactive inhibition; the author demonstrates that the recall of new information decreases (i.e. proactive inhibition increases) with a higher degree of learning of old information. The author, in (Underwood 1945), further shows that proactive inhibition increases with an increase in the quantity of information. However, this effect was transient and seen only in initial recalls, suggesting a stronger occurrence of proactive inhibition in short-term memory (Keppel and Underwood 1962; Loess 1964). The potential for familiarity-based recall inhibition is further highlighted by the Part Set Cue Theory (Nickerson 1984) which suggests that the repeated exposure to and recall of a partial set of information inhibits the retrieval of the remaining information that comprises the set. Therefore, in the context of DfAM education, students' familiarity with and repeated recall of restrictive DfAM – through previous formal and informal experiences with AM – could inhibit their learning of opportunistic DfAM concepts.

In light of these findings, it is important for DfAM education to take into account the order when presenting opportunistic and restrictive DfAM, especially in short-duration teaching interventions. Variations in the order could influence and potentially interfere with students' learning and use of certain concepts in their design process. This issue is further highlighted in the case of novice designers who are primarily exposed to restrictive DfAM, often in lower intensity and informal settings. However, there is a need to explore this effect of the order of content on DfAM learning and use and the creativity of the associated design outcomes. Before doing so, current practices in AM and DfAM education are reviewed and discussed.

2.3. Current strategies in AM and DfAM education

To address the need for a workforce skilled in AM, several researchers have presented educational interventions for DfAM education, some of which are reviewed by Ford and Minshall (2019). These interventions can broadly be classified into three types: (1) formal, in-class interventions, (2) informal, self-learning initiatives, and (3) design tools and frameworks (see [Yang and Zhao 2015; Pradel et al. 2018b]). In this section, we review formal educational interventions that introduce designers to dual DfAM. Additionally, we review informal educational initiatives as these experiences often expose students to partial sets of DfAM concepts.

Ferchow, Klahn, and Meboldt (2018) present a workshop which uses the experience transfer model of learning (Leutenecker-Twelsiek et al. 2017) to transfer DfAM skills from research to practicing designers. In this workshop, designers are given input lectures on AM and DfAM while they apply this knowledge in the conceptual and detailed design of an AM part. The lectures – tailored to the stages of the design project – first introduce designers to the various AM processes. This is followed by an introduction to DfAM principles, manufacturing and build preparation, and metal microstructure considerations, in that order. Diegel, Nordin, and Motte (2019) present a 4-day hands-on workshop for training industry professionals in DfAM. Each day of the discussed workshop introduces participants to some combination of opportunistic and restrictive DfAM concepts followed by design exercises. For example, on day 3, participants are introduced to support material removal and part consolidation.

Additionally, Prabhu et al. present a series of lecture-based studies comparing dual DfAM education to restrictive DfAM education. They identify the role of design task definition in encouraging creativity through dual DfAM education in (Prabhu et al. 2020a). Furthermore, they observe that dual DfAM training encourages designers to generate more AM-appropriate designs (Prabhu et al. 2020e); however, they also observe that dual DfAM education could affect designers' integration of restrictive DfAM concepts such as support material accommodation (Prabhu et al. 2020d). The authors, in (Prabhu et al. 2020f), also observe that the competitive structure of design tasks influences designers' creativity. Specifically, they demonstrate that designers trained in dual DfAM generate solutions of higher creativity compared to only restrictive DfAM training, but only when presented with a competitive design task. Finally, Prabhu, Bracken, et al. (2020) extend these findings to demonstrate the effectiveness of lecture-based DfAM workshops towards encouraging creativity among industry practitioners. These studies suggest the potential for dual DfAM education to both, encourage and hamper creativity and DfAM integration in designs. To encourage successful integration of DfAM, designers must retrieve the appropriate DfAM concepts at the various stage(s) in the design process. As discussed in Section 2.2, the order of presenting information influences the recall of this information, and limited research has explored this effect in dual DfAM education.

In addition to these formal interventions, numerous efforts have been made to provide students with informal access and exposure to AM technologies. For example, several academic institutions have set up maker-spaces both on and off-campus to provide students with access to AM and encourage learning by doing. Some examples include the 3D printing vending machine at UT Austin (Kuhn et al. 2014) and the maker spaces at Penn State ("Submitting Your 3D Print | Maker Commons" n.d.), Georgia Tech ("Tips for Designing a 3D Printed Part | Innovation Station" n.d.), MIT ("3D Printing Service - MIT Project Manus" n.d.), and Case Western ("3D Printing Services | Case School of Engineering" n.d.). These makerspaces provide students with the opportunity to interact with AM machines either directly or through online interfaces. Additionally, some of the makerspaces also provide students with design and build preparation guidelines; however, a majority of these instructional resources are focused on preventing build failure through restrictive DfAM. As presented in Section 2.2, one's familiarity with a partial set of information – in this case, restrictive DfAM – can result in the inhibited recall of the remaining information, i.e. opportunistic DfAM. This recall of opportunistic DfAM could further be influenced by the order of presentation of dual DfAM and limited research has explored this effect. Therefore, our aim in the present research is to explore this gap in the literature through an experimental study. In the next section, we present the research questions we seek to answer to explore this gap in the literature.

3. Research questions

As discussed in Section 2, little prior research has explored the effects of the order of presenting opportunistic and restrictive DfAM content on students' learning, DfAM use, and creativity. This investigation is important because, as discussed in Section 2.2, the order of presenting information has been shown to influence individuals' learning and recall of said information. Our goal in this study is to explore this research gap and to investigate the effect of variations in the order of presenting opportunistic and restrictive DfAM content on students' learning and use of DfAM and the creativity of their design outcomes. Specifically, we explored the following research questions (RQs):

- *RQ1: How does the order of presenting DfAM educational content affect the participants' self-efficacy with the various DfAM concepts?* Prior research has demonstrated that students find it easier to learn about restrictive DfAM compared to opportunistic DfAM (Prabhu et al. 2020b). Students also have been shown to demonstrate a greater familiarity and exposure to restrictive DfAM potentially due to their prior informal experiences with AM (Prabhu et al. 2018). Therefore, based on Part-Set Cue Theory (Nickerson 1984), we hypothesise that introducing opportunistic DfAM followed by restrictive DfAM could result in retroactive inhibition, therefore limiting the increase in students' opportunistic DfAM self-efficacy.
- *RQ2: How does the order of presenting DfAM educational content affect the participants' self-reported emphasis on the various DfAM concepts?* Similar to the hypothesis in RQ1, given students' familiarity and ease of learning restrictive DfAM, we hypothesise that introducing opportunistic DfAM followed by restrictive DfAM would result in a lower self-reported emphasis on opportunistic DfAM.
- *RQ3: How does the order of presenting DfAM educational content affect the creativity of participants' design outcomes?* Prior research has demonstrated that the application of opportunistic DfAM correlates with greater design creativity (Blösch-Paidosh, Ahmed-Kristensen, and Shea 2019). Building up on the hypotheses of the first two RQs, we hypothesise that teaching opportunistic DfAM followed by restrictive DfAM would inhibit students' recall of opportunistic DfAM, thus limiting the application of these concepts in design. This would result in the generation of ideas of lower creativity compared to teaching restrictive DfAM followed by opportunistic DfAM.

4. Experimental methods

To answer these questions, we conducted an experiment that consisted of a short-duration intervention lecture and a DfAM challenge and the details of the experiment are discussed next.

4.1. Participants

The experiment was conducted at a large northeastern public university, where participants ($N = 263$ not accounting for missing data) were recruited from a junior-level mechanical engineering course that focused on product design and engineering design methods. The experiment was conducted in both the fall and spring semesters, and in Table 1, we provide a breakdown of participants based on their year of study. As presented in the table, we observed similar distributions in participants' year of study in the two semesters, with a majority of the participants being in their junior year of study. This is a possible limitation of our study and future research must extend our findings towards comparing effects of DfAM education on students in different years of study (e.g. freshmen, seniors, and graduate students) as recommended by Prabhu et al. (2018). The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study (see Figure 1), and the distribution of participants' previous AM and DfAM experiences were similar between the two semesters. Moreover, we performed a between-subjects analysis in this study and since year of study and prior experience were not variables of interest, these variables were not considered in our analysis.

4.2. Procedure and metrics

The experiment consisted of three stages: (1) a pre-intervention survey, (2) a series of DfAM educational intervention lectures, and (3) a DfAM task followed by a post-intervention survey. The study was reviewed and approved by the Institutional Review Board of the

Table 1. Distribution of participants based on their year of study.

	Fall semester	Spring semester
Sophomores	0	4
Juniors	84	134
Seniors	26	15
Missing	0	0
Total	110	153

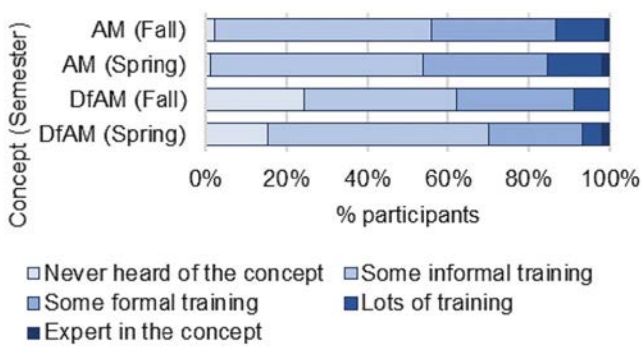


Figure 1. Distribution of participants' previous experience.

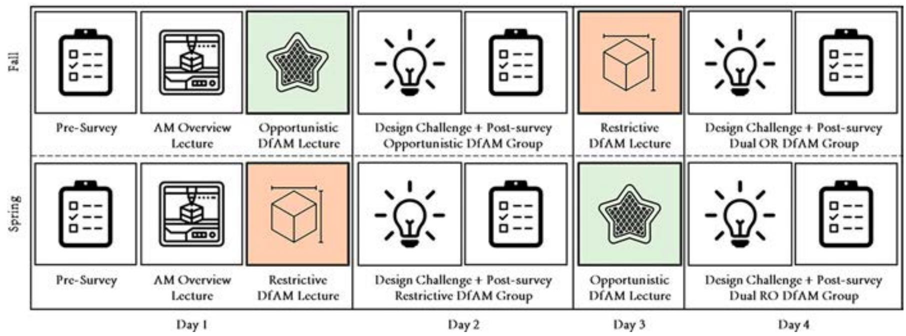


Figure 2. Summary of the experimental procedure.

university, and implied consent was obtained from the participants prior to the experimentation in both semesters. In Figure 2, we summarise the overall flow of events in both semesters.

4.2.1. Stage 1: pre-intervention survey

For the first stage of the experiment, the participants were asked to complete a pre-intervention survey. The survey collected their previous experience in AM and DfAM (see Figure 1) and their DfAM self-efficacy. Self-efficacy was used as a measure in this study as previous research has demonstrated the role of self-efficacy (Bandura 1977) and meta-cognition (Bransford, Brown, and Cocking 1999) in predicting effective learning. Participants were asked to respond to the self-efficacy survey from (Prabhu et al. 2020b). The survey focuses on both the opportunistic and restrictive DfAM domains and uses a 5-point scale derived from Bloom's Taxonomy (Bloom et al. 1966). The internal consistency of the scale was assessed by performing a reliability analysis, and a high Cronbach's α (Cronbach 1951) was observed (pre-intervention $\alpha = 0.91$, post-intervention $\alpha = 0.87$). Similarly, the individual opportunistic and restrictive sections of the scale also showed a high internal consistency, as determined by Cronbach's α (opportunistic: pre-intervention $\alpha = 0.86$, post-intervention $\alpha = 0.75$, and restrictive: pre-intervention $\alpha = 0.86$, post-intervention $\alpha = 0.81$).

4.2.2. Stage 2: DfAM educational intervention

Next, participants were introduced to the DfAM educational content through a series of lectures (see Figure 2). Participants in the spring semester were trained in either (1) restrictive DfAM ($N_R = 63$) or (2) restrictive followed by opportunistic (dual R-O) DfAM ($N_{R-O} = 41$). On the other hand, participants in the fall semester were trained in either (1) opportunistic DfAM ($N_O = 45$) or (2) opportunistic followed by restrictive (dual O-R) DfAM ($N_{O-R} = 46$).

All participants in each semester were first given a 20-minute lecture providing an overview of AM. In this lecture, the instructor discussed topics such as (1) introduction to the material extrusion process – the AM process available to the students in the AM design challenge, (2) contrasts between additive and subtractive manufacturing, (3) the digital thread, (4) the Cartesian coordinate system as it relates to the print volume, and (5) materials available in material extrusion. After the AM overview lecture, participants were introduced to the DfAM content. The 20-minute restrictive DfAM lecture covered: (1) build time, (2) feature size, (3) support material, (4) anisotropy, (5) surface finish, and (6) warping. On the other hand, the 20-minute opportunistic DfAM lecture comprised: (1) geometric complexity, (2) mass customisation, (3) part consolidation, (4) printed assemblies, (5) multi-material printing, and (6) embedding. The lecture slides can be accessed at [redacted]. We used short-duration intervention lectures to ensure that we completed all stages of the experiment within the allotted class time. While researchers have argued for the effectiveness of such lecture-style DfAM interventions (e.g. see [Ferchow, Klahn, and Meboldt 2018]), we acknowledge the need to extend this experiment in future work to investigate the effects of a longer intervention lecture where students are introduced to the various DfAM concepts in detail.

4.2.3. Stage 3: DfAM task and post-intervention survey

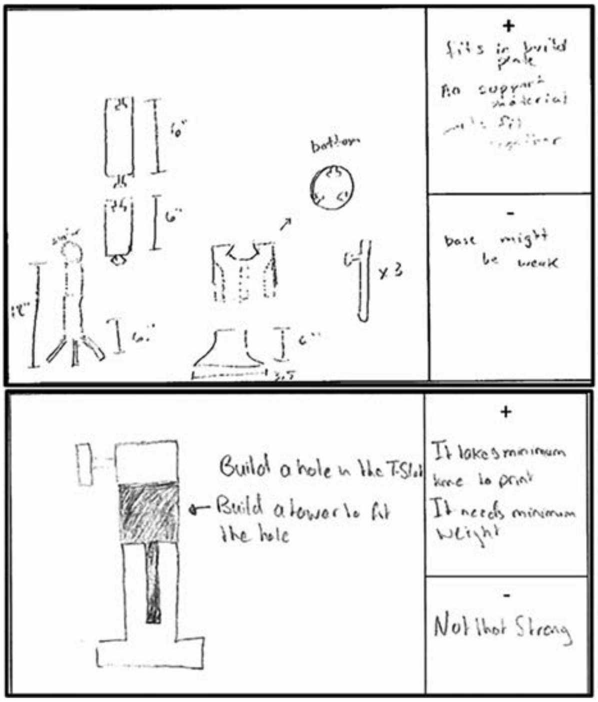
For the final stage of the experiment, the participants were asked to individually participate in a DfAM task. The wind-turbine design prompt from (Prabhu et al. 2020a) was used in the experiment as it requires minimal domain-specific knowledge beyond AM (as suggested by Amabile [1996]). Furthermore, the design problem was chosen given its ability to encourage creativity in DfAM (Prabhu et al. 2020a). Participants from both semesters were informed that the best performing design (in terms of build material and time) from each section would receive a $20 gift card. This competition structure was chosen based on preliminary findings that show the effectiveness of competitions in encouraging creativity in DfAM tasks (Prabhu et al. 2020f).

During the design challenge, participants were first asked to individually brainstorm for ideas using both sketches and words to describe their ideas. Participants were also asked to evaluate each idea by noting down its strengths and weaknesses. Next, the participants were asked to individually develop a final design with the freedom to redesign or combine previous ideas or brainstorm again. These individual final designs were assessed for their creativity as part of this experiment.

The participants' final individual designs from the task were assessed for their creativity using the Consensual Assessment Technique (CAT) (Hennessey 1994; Baer and McKool 2016). Two quasi-experts with a background in AM and DfAM (as suggested by Kaufman and Baer [2012]; Kaufman et al. [2013]) independently rated the designs on a scale of 1 = least creative to 6 = most creative using the following metrics (as suggested by the three-factor model [Besemer 1998; Besemer and O'Quin 1999]):

- *Uniqueness*: Measures the originality of each design idea compared to other ideas generated in the sample (Amabile 1996).
- *Usefulness*: Measures the idea's ability to solve the given design problem along with its value and appropriateness.
- *Technical Goodness*: Measures the suitability of a design idea with respect to the AM processes, both in terms of capabilities and limitations (Prabhu et al. 2020b, 2020e).
- *Overall Creativity*: Provides a subjective evaluation of the overall creativity of a design idea (Kaufman et al. 2013).

A moderate to high inter-rater reliability was observed between scores of the two raters, as verified by an Intraclass Correlation Coefficient of 0.77 (Cronbach 1951). An average score



Participant ID	TEER11
Uniqueness	4.25
Usefulness	4.25
Technical Goodness	5.25
Overall Creativity	5

Participant ID	DAAH12
Uniqueness	2
Usefulness	2
Technical Goodness	1.75
Overall Creativity	1.5

Figure 3. Example of participants' ideas from the design challenge and their assigned CAT scores (1 = least creative and 6 = most creative).

for each metric was then calculated by taking a mean of the scores from the two raters for each design. Examples of ideas generated by the participants and their assigned creativity scores are presented in Figure 3.

Figure 3 Example of participants' ideas from the design challenge and their assigned CAT scores (1 = least creative and 6 = most creative)

Upon completing the final individual designs, participants were asked to self-report the emphasis they gave to the different DfAM techniques during the AM design challenge. The scale developed by Prabhu et al. (2020e) was used to measure the self-reported emphasis, and participants were asked to report the importance they gave to each DfAM technique on a 5-point Likert-type scale, with 1 = 'Not important at all' to 5 = 'Absolutely essential'. Students were then split into groups, asked to pick an idea to represent the group and generate CAD models for this idea. The group and CAD portions of the experiments were part of a larger study and are not considered in this paper. Finally, participants were asked to complete a post-intervention survey with the same DfAM self-efficacy questions as given in the pre-intervention survey.

5. Data analysis and results

To answer the three research questions posed in Section 3, statistical analyses were performed using a significance level of $\alpha = 0.05$ and a 95% confidence interval. A sample size of 195 (compared to 263 in the original sample) was used for the analyses, of which,

(1) $N_R = 63$ received restrictive DfAM only, (2) $N_{R-O} = 41$ received restrictive followed by opportunistic (dual R-O) DfAM, (3) $N_O = 45$ received only opportunistic DfAM, and (4) $N_{O-R} = 46$ received opportunistic followed by restrictive (dual O-R) DfAM. It should be noted that participants with significant missing values were list-wise deleted for analysis of the individual research questions. Non-parametric tests were used for RQ1 and RQ2 given the difference in sample sizes and all assumptions were tested as noted. It should also be noted that our sample size was limited by the number of consenting participants recruited from the course; however, a post-hoc power analysis using G∗Power (Faul et al. 2007) (fixed-effects, omnibus, one-way) with a medium effect size ($f = 0.25, \alpha = 0.05, N = 195$, number of groups $= 4$) revealed a power of 0.84. All reported results are either mean (M) ± standard deviation or median (Mdn) unless otherwise specified.

5.1. RQ1: how does the order of presenting DfAM educational content affect the participants' self-efficacy with the various DfAM concepts?

To answer the first research question, a series of repeated measures Wilcoxon Signed Rank tests (Wilcox 2011) was performed. The pre- and post-intervention self-efficacy scores were taken as the within-subjects' factors, and an independent analysis was conducted for each educational intervention group. The results of the analysis are summarised in Figure 4. As seen in the figure, participants from all four educational intervention groups show an increasing trend in their restrictive DfAM self-efficacy; however only groups that received opportunistic DfAM training (i.e. the opportunistic only and the two dual DfAM groups) demonstrated an increase in their opportunistic DfAM self-efficacy.

Next, to investigate the effect of the order of lectures on the participants' DfAM self-efficacy, a series of Mann–Whitney U tests (Mann and Whitney 1947) were performed comparing the change scores (i.e. the difference between pre- and post-intervention scores) between the two dual DfAM groups. The results showed a significant effect of the order of lectures on the change in self-efficacy with mass customisation, $z = 2.57$, $U = 1230.00$, $p = 0.01$, with the dual O-R group demonstrating a greater increase in self-efficacy ($Mdn = 1.00$) compared to the dual R-O group ($Mdn = 0.00$). No differences were seen in the changes in self-efficacies with the other DfAM concepts. The implications of these results are discussed in Section 6.

5.2. RQ2: how does the order of presenting DfAM educational content affect the participants' self-reported emphasis on the various DfAM concepts?

To answer the second research question, a series of independent samples median tests were performed. A median test was chosen (as opposed to an ANOVA) due to the ordinal and non-normal nature of the data. The participants' self-reported emphasis on each DfAM concept was compared against the pooled median for the DfAM concept, and the DfAM educational group was taken as the independent variable. A sample size of 175 (as opposed to 195 in RQ1) was used for this analysis due to list-wise missing values, and data from participants with significant missing responses were entirely deleted. The results showed a significant effect of the educational intervention group on the participants' self-reported emphasis on mass customisation (χ^2 (3) $= 12.16$, $p = 0.01$), part

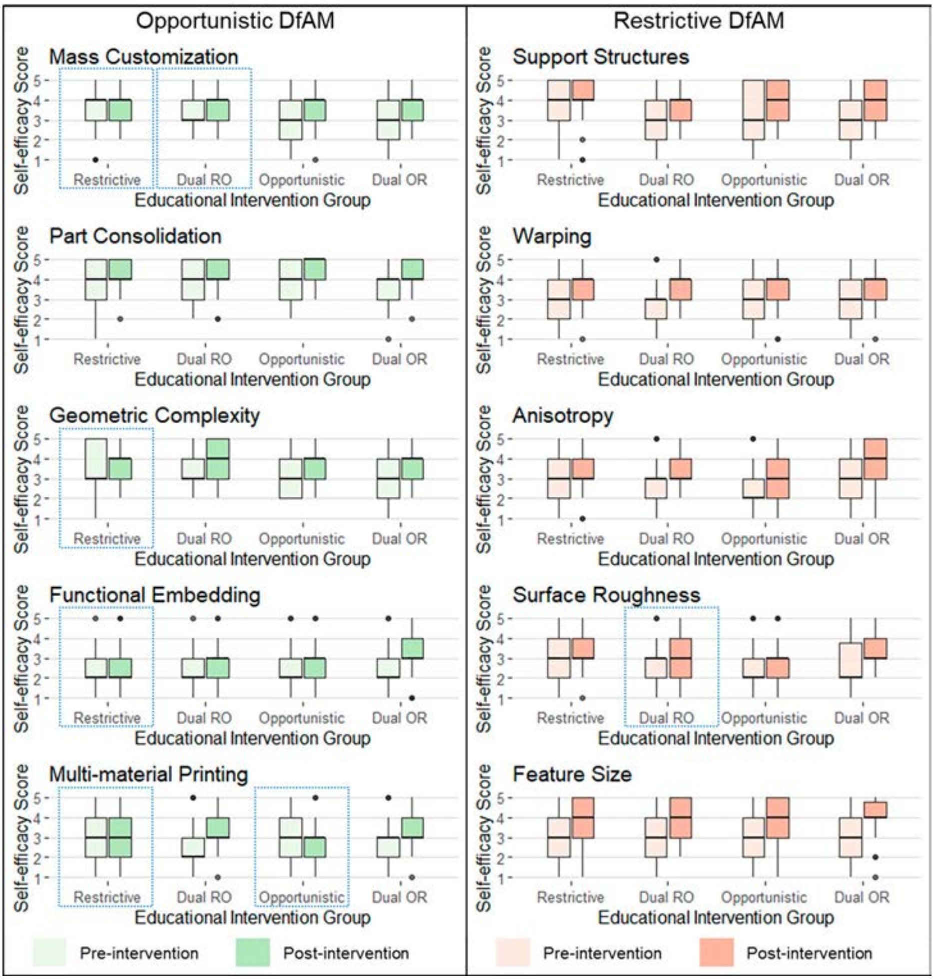


Figure 4. Changes in participants' DfAM self-efficacy (non-significant changes are highlighted).

consolidation (χ^2 (3) = 8.91, $p = 0.03$), functional embedding (χ^2 (3) = 8.99, $p = 0.03$), and multi-material printing (χ^2 (3) = 8.00, $p = 0.046$). No significant effects were seen in the case of the restrictive DfAM concepts.

Pairwise comparisons within the independent samples median test showed that participants from the dual O-R DfAM group gave a significantly higher emphasis on mass customisation (*Mdn* = 3) and multi-material design (*Mdn* = 2) compared to the restrictive DfAM group (*Mdn* = 2 and 1 respectively), $p_{adj} < 0.05$. These differences are labelled as D1 and D2 in Figure 5. On the other hand, participants from the restrictive DfAM group gave a significantly higher emphasis on part consolidation (*Mdn* = 5) compared to the dual OR DfAM group (*Mdn* = 4), $p_{adj} < 0.05$. This difference is labelled as D3 in Figure 5. No significant differences were seen between the two dual DfAM groups. The pair-wise comparisons for significant results are summarised in Figure 5, and the implications of these results are discussed in Section 6.

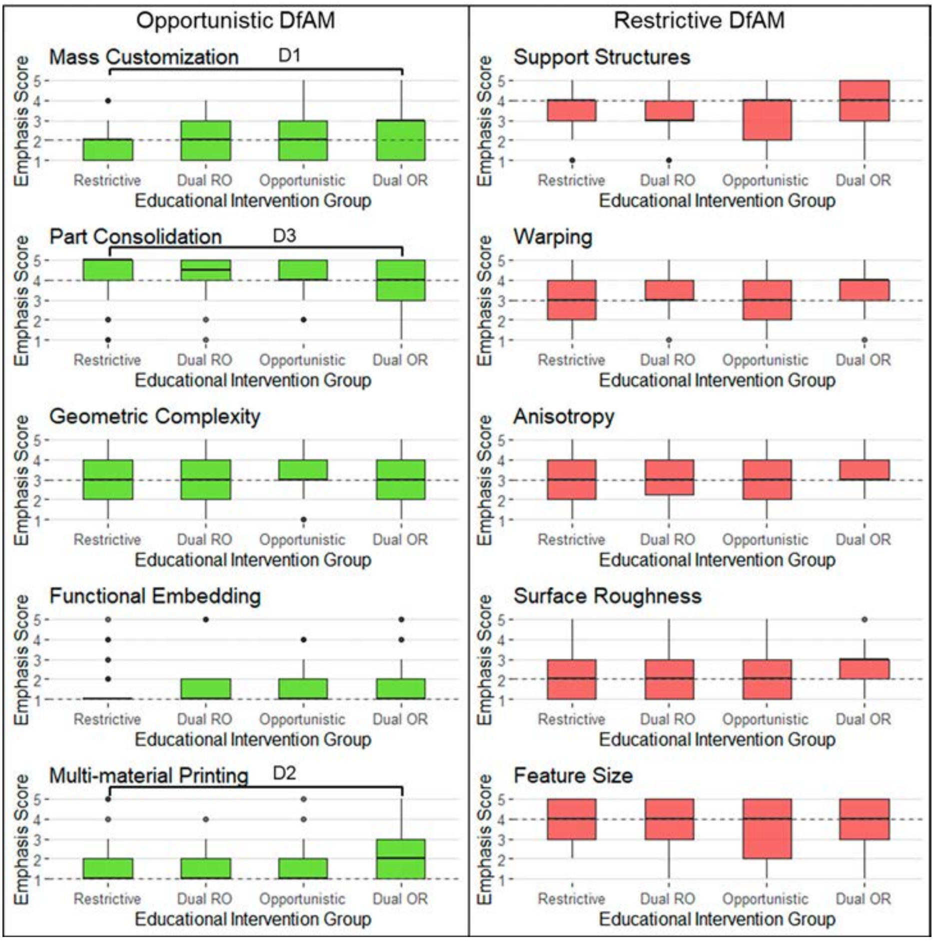


Figure 5. Pairwise comparisons of participants' self-reported DfAM emphasis across educational intervention groups (dashed line indicates the overall median and significant differences at $p < 0.05$ are denoted as D1, D2, and D3).

Figure 5 Pairwise comparisons of participants' self-reported DfAM emphasis across educational intervention groups (dashed line indicates the overall median and significant differences at $p < 0.05$ are denoted as D1, D2, and D3)

5.3. RQ3: how does the order of presenting DfAM educational content affect the creativity of the participants' design outcomes?

To answer the third research question, one-way ANOVAs were performed with each component of creativity – uniqueness, usefulness, technical goodness, and overall creativity – as the dependent variables and the DfAM educational group as the independent variable. Before performing this analysis, the assumptions of the test were verified. There were no outliers exceeding three standard deviations, and while there was homogeneity of variances for usefulness, uniqueness, and technical goodness ($p > 0.05$), this assumption was violated for overall creativity ($p < 0.05$). Further, although the assumption of normality – as

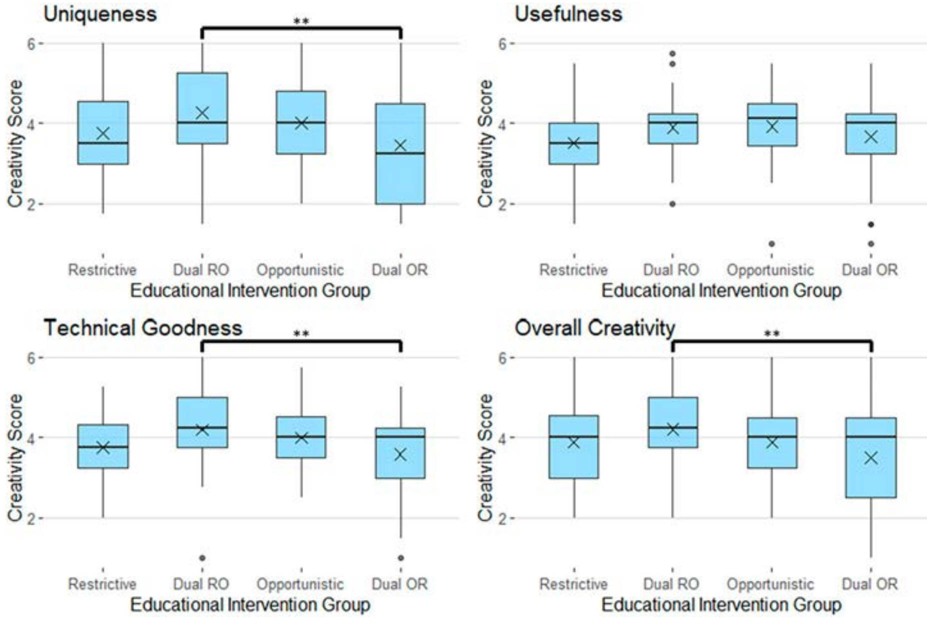


Figure 6. Summary of creativity scores across educational intervention groups ($**p < 0.05$).

assessed by the Shapiro–Wilk test (Shapiro and Wilk 1965) – was violated for some variables, the analysis was performed given the robustness of the test to deviations from normality. Two data-points were removed due to missing/illegible designs leading to a total sample size of 193.

The results of the ANOVA showed a statistically significant effect of educational intervention group on idea uniqueness ($F(3,190) = 4.01$, $p = 0.01$, $\eta_p^2 = 0.06$), technical goodness ($F(3,190) = 4.28$, $p = 0.01$, $\eta_p^2 = 0.06$), and overall creativity ($F(3,190) = 3.29$, $p = 0.02$, $\eta_p^2 = 0.05$). However, the results showed no significant effect of educational intervention group on the usefulness of the ideas ($F(3,190) = 2.63$, $p = 0.05$, $\eta_p^2 = 0.04$). Tukey's post-hoc tests (Tukey 1949) were performed on the significant effects and plotted in Figure 6. The results showed that the dual R-O DfAM group generated ideas of significantly higher uniqueness, technical goodness, and overall creativity, compared to the dual O-R DfAM group ($p < 0.05$). No other significant pair-wise differences were observed. The implications of these results and the findings for the other RQs are discussed in the next section.

6. Discussion and implications for design education

Our goal in this research is to understand the effect of the order of information in a DfAM educational intervention on students' learning and use of DfAM and its resulting effects on students' creativity. The key findings from the research are:

6.1. Students must explicitly be trained in opportunistic DfAM to result in an increase in their opportunistic self-efficacy

The first key finding from the results was that students from all four educational intervention groups demonstrated an increase in their restrictive DfAM self-efficacy and this increase was seen even among those who received only opportunistic DfAM education. On the other hand, only students trained in opportunistic DfAM, either with or without restrictive DfAM, present a positive change in their self-efficacy with these concepts while those trained only in restrictive DfAM do not. This result corroborates prior findings (e.g. [Prabhu et al. 2020b]) in that students show a greater increase in restrictive DfAM self-efficacy compared to opportunistic DfAM. This greater increase could either be attributed to participants' prior informal experience in AM and DfAM (see Figure 1) or more likely due to the similarity between restrictive DfAM and traditional DfMA.

This finding suggests that despite not being explicitly trained in restrictive DfAM, students demonstrate some knowledge about these topics, possibly gained through their prior formal and informal learning experiences (see Figure 1). Introducing students to DfAM – either opportunistic, restrictive, or both – potentially results in the retrieval of this restrictive DfAM knowledge, thus reinforcing their perceived efficacy in these techniques. However, this effect was not seen in the case of students' opportunistic DfAM self-efficacy; only those trained in opportunistic DfAM – with or without restrictive DfAM – showed an increase in their self-efficacy with these DfAM concepts. This result, therefore, suggests that students have limited exposure to opportunistic DfAM through their prior AM and DfAM experience and must explicitly be trained in these opportunistic aspects of DfAM. This training would inform students about the various capabilities of AM, and this awareness has been identified as a key characteristic of successful AM engineers (Simpson, Williams, and Hripko 2017). This need for emphasis on opportunistic DfAM training is also supported by the similarity between limitation-based restrictive DfAM concepts and limitation-focused traditional DfMA techniques – the current standard for design for manufacturing integration. DfAM training must encourage students to integrate their knowledge of manufacturing beyond accommodating the limitations of these processes towards adopting a dual approach accounting for both, the capabilities and the limitations of manufacturing processes.

The second key finding was that the order of the lectures did not have a significant effect on students' self-efficacy with the various DfAM concepts. This finding suggests that students' DfAM self-efficacy is not affected by either retroactive or proactive interference caused by the order of presentation of content. However, we must be careful in making this inference since the self-efficacy scale used in this study captures students' comfort and familiarity with the various DfAM concepts and not necessarily their ability to *recall* these concepts, whether with or without cues. This distinction is important as prior research has demonstrated that individuals demonstrate superior performance in familiarity and recognition tasks compared to recall tasks (Yonelinas 2002). Therefore, future research must investigate whether or not the absence of memory interference can be extended to recall tasks such as knowledge tests.

6.2. Order of dual DfAM training influences participants' self-reported emphasis on DfAM when compared against restrictive DfAM training

The third key finding from the study was that the order of the dual DfAM education influenced students' emphasis on opportunistic DfAM concepts, but only when compared against participants who received only restrictive DfAM education. Specifically, we see that participants trained in dual O-R DfAM gave a significantly higher emphasis on the opportunistic DfAM concepts of mass customisation and multi-material design. This finding suggests that introducing opportunistic DfAM first followed by restrictive DfAM is more successful in encouraging an application of certain opportunistic DfAM concepts. This result corroborates prior findings where students have shown to give a greater emphasis on restrictive DfAM compared to opportunistic DfAM (Prabhu et al. 2020e) and suggests that opportunistic DfAM education shifts this emphasis to dual DfAM. This could either be attributed to restrictive DfAM's similarity to traditional DfMA, or due to students' prior exposure to restrictive DfAM, resulting in an inhibition to recall opportunistic DfAM. This result further validates the findings of the first research question which suggested the need for explicit dual DfAM training to encourage designers to integrate opportunistic DfAM in designs.

However, we also see from the results that compared to other forms of DfAM education, participants trained only in restrictive DfAM gave the highest emphasis on part consolidation – an important DfAM concept considering the constraints and objectives of the design challenge. The design challenge tasked students with developing a tower at least 18″ tall that could be built in a single 11.6″ × 7.6″ × 6.5″ build volume. The constraint-based nature of restrictive DfAM training could have shifted participants' focus on the constraints of the design problem, which in turn could have resulted in a greater emphasis on part consolidation – an opportunistic DfAM concept – to satisfy the design constraints. This is an interesting finding as it suggests that restrictive DfAM training encourages students to give a greater emphasis on design constraints and potentially employing part consolidation techniques to overcome them. However, the participants self-reported their emphasis on the various DfAM concepts, and given the relatively low reliability of self-report scores, we must be careful in making these inferences.

6.3. *Teaching restrictive DfAM first followed by opportunistic DfAM results in the generation of ideas with higher creativity*

The final key finding from the study was that the order of presenting dual DfAM content affected the uniqueness, technical goodness, and overall creativity of the participants' designs. Specifically, we see that participants presented with dual R-O DfAM generated ideas of higher creativity compared to those presented with dual O-R DfAM. This is a surprising and novel finding as it evaluates the effect of the order of presenting DfAM content on students' recall and DfAM use without relying on familiarity-driven self-reported scores.

Prior research has demonstrated that the integration of opportunistic DfAM positively correlates with the uniqueness and creativity of designs (Blösch-Paidosh, Ahmed-Kristensen, and Shea 2019). Therefore, the higher creativity of the ideas generated by the dual R-O group suggests that the order of the lectures influences participants' retrieval and integration of opportunistic DfAM in their designs. This could be attributed to the retroactive inhibition (Britt 1935) – students' learning of restrictive DfAM following opportunistic DfAM could have interfered with their recall of opportunistic DfAM. This could further have been aggravated by participants' familiarity with a partial set of DfAM concepts, i.e. restrictive DfAM, as suggested by Part-Set Cue Theory (Nickerson 1984). Students' familiarity with restrictive DfAM – as seen in the first RQ – potentially due to their prior experiences with AM could further interfere with their learning and recall of opportunistic DfAM. This finding could also be attributed to the recency effect (Tzeng 1973) – since opportunistic DfAM was taught temporally closer to the design challenge, it could have been freshly consolidated in memory and therefore easily recalled. Furthermore, the results show that participants from the dual R-O DfAM group not only generated ideas of high uniqueness and overall creativity, but their ideas also showed higher technical goodness compared to ideas generated by participants from the dual O-R group. This outcome further reinforces the inference that the greater creativity of participants' designs could be attributed to DfAM integration, especially opportunistic DfAM integration, in the designs.

However, this finding conflicts the findings from RQ2 where participants from the dual O-R DfAM group reported a greater emphasis on the opportunistic DfAM concepts of mass customisation and multi-material design. This difference suggests a potential disparity between students' self-reported use of DfAM – particularly opportunistic DfAM – and their actual integration of these techniques in designs. This disparity is particularly highlighted by the lack of relevance of the DfAM techniques of mass customisation and multi-material design to the design task. Students do not have access to multi-material AM technologies through the Penn State Maker Commons. Additionally, the objectives and constraints of the design problem present limited potential for mass customisation of designs. Therefore, future research should compare how students' self-reported DfAM use corresponds to an external and objective assessment of their designs using metrics such as in (Prabhu et al. 2020d).

These findings suggest that students' prior AM experience – particularly with restrictive DfAM could interfere with their opportunistic DfAM integration in design, thereby influencing the creativity of their designs. Prior research has demonstrated the effectiveness of repeated rehearsal (Linton 1982) and deep encoding in enhancing retrieval. Therefore, educators must ensure that students are encouraged to repeatedly rehearse the various opportunistic DfAM concepts. Additionally, educators are also encouraged to ensure that students deeply encode the various opportunistic DfAM concepts. This could be achieved through targeted elaboration and synthesis (Fisher and Craik 1980) where students are encouraged to actively apply the various DfAM concepts. These strategies could help prevent students' knowledge of and familiarity with restrictive DfAM from interfering with their recall and integration of opportunistic DfAM. This deep encoding could also be achieved by spreading the intervention over longer durations to give the students an opportunity to consolidate these concepts in their memory (Cepeda et al. 2006, 2008, 2009).

7. Conclusion, limitations, and future work

Our aim in this research was to investigate the effect of the order of presenting dual DfAM content on students' DfAM self-efficacy, their self-reported emphasis on DfAM, and the creativity of their design outcomes. The results showed that all students trained in DfAM – opportunistic, restrictive, or both – demonstrate an increase in their restrictive DfAM self-efficacy. In contrast, students must explicitly be introduced to opportunistic DfAM concepts to increase self-efficacy in opportunistic DfAM during a task-based educational intervention. This finding suggests that engineering design students demonstrate greater ease in developing restrictive DfAM self-efficacy – a finding observed in previous research (Prabhu et al. 2020b). Further, the results show that while dual DfAM education results in a greater self-reported emphasis on mass customisation and multi-material design compared to restrictive DfAM, this was true only for those trained in dual OR DfAM. Finally, we see that students who were introduced to dual R-O DfAM generated ideas of higher creativity and technical goodness compared to those who received dual O-R DfAM training. Given the potential role of opportunistic DfAM in encouraging creativity (Blösch-Paidosh, Ahmed-Kristensen, and Shea 2019), this could be attributed to a hindered recall of opportunistic DfAM caused by retroactive interference due to restrictive DfAM knowledge. Therefore, educators are recommended to encourage deeper learning and recall of opportunistic DfAM aspects to minimise interference due to restrictive DfAM, and this could potentially be achieved through repeated rehearsal and targeted application of opportunistic DfAM.

Despite providing important insights on the potential effects of the order of presenting DfAM content on students' design outcomes, this research has several limitations. First, the study used a lecture-style delivery of content where students are introduced to the various DfAM concepts through 20-minute lectures on opportunistic and restrictive DfAM. This rapid and condensed introduction of content could have limited students' learning of the various DfAM concepts as prior research has demonstrated the higher effectiveness of temporally-spaced learning (Cepeda et al. 2008, 2009, 2006). Therefore, future research must extend this study to include interventions spaced over several sessions and longer durations. Second, the study uses a single design challenge as a hands-on learning experience for several DfAM concepts together. Therefore, in addition to expanding the input lectures, future research must also employ multiple design challenges, therefore, resulting in a targeted application and rehearsal of the various DfAM concepts. Such a study could also explore the use of different design tasks for the various DfAM concepts as suggested by Prabhu et al. (2020b). Third, the study primarily assesses students' learning and application of DfAM in the concept generation stage. However, different DfAM processes could play a different role in the various stages of engineering design such as concept evaluation and selection. Therefore, future research must explore whether or not variations in students' use of DfAM are based on the various stages of design and the consequent effect on the designs. Fourth, the participants in the study primarily comprised juniors and seniors; future research must extend our findings to compare the effects of DfAM education on designers with varying levels of prior experience in engineering, AM, and DfAM. Finally, the study uses AM technical goodness – a subjective measure – to assess students' integration of DfAM in their designs. While this measure provides a useful overall assessment of DfAM integration, future research must employ specific objective measures for capturing students' DfAM integration. The use of objective measures could highlight variations in students' learning of the various DfAM concepts, as well as variations in the influence of DfAM on design creativity.

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