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Comparing parallel and iterative prototyping strategies during engineering design

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Abstract
Prototyping, whether physical, virtual, or computational, is an important step in the engineering design process. Iterative prototyping strategies are commonly taught in engineering curricula and implemented in industry, but there may be other ways to approach the prototyping process. Engineers often use physical prototypes to learn about their designs, communicate ideas, and validate effectiveness. In this study, the effects of iterative and parallel prototyping strategies are compared through a design competition with a heavy focus on gaining knowledge from the physical models. Design success, engineering design self-efficacy, and solution space exploration are considered to evaluate the different effects of these two prototyping strategies. Results suggest that a parallel prototyping strategy yields greater design success, increased confidence and reduced anxiety when conducting engineering design, and greater exploration of the solution space. In addition, participants seem largely unaware of these benefits based a post-prototyping survey. This work shows the value of parallel prototyping, which has implications for how prototyping is taught to engineering novices and how engineering designers in industry should approach the prototyping process. This study also provides strong evidence for a need to study the benefits and drawbacks of a parallel prototypin approach in more complex situations.

Keywords Prototyping · Parallel · Iterative · Self-Efficacy · Design Theory · Design Methodology · Engineering Design

1 Introduction

During the engineering design process, prototypes provide valuable feedback about the form, function, aesthetics, feasibility, and value of a product or engineering system. The prototyping process involves a systematic investigation into a design concept as a development strategy and helps designers plan an engineering design project that successfully meets requirements and validates designers' decisions (Otto and Wood 2001; Pahl and Beitz 2013; Ulrich and Eppinger 2015; Dieter and Schmidt 2009). Many articles support an iterative approach to prototyping as a central tenet of the engineering design process that improves the quality and success of a design project (Hartmann et al. 2006; Marks and Chase 2019; Camburn 2015; Camburn, Jensen, et al. 2015; Dow, Heddleston, and Klemmer 2009). While iteration is clearly an important aspect of the prototyping process, some studies have considered the benefits of a parallel approach to the prototyping process (Dow et al. 2010; Dow et al. 2009a, b; Jensen et al. 2017; Hansen and Özkil 2020). Parallel prototyping involves the exploration of different concepts considered simultaneously to explore a broader region of the possible solution space. Purposefully implementing an iterative strategy, a parallel strategy, or combination of both strategies may have different effects on design outcome. Research has shown the benefits of leveraging different prototyping strategies with effects on new product success as related to cost and time for development (Thomke 1998; Dahan and Mendelson 2001; Srinivasan et al. 1997).

While iterative prototyping is likely inherent in all prototyping strategies to some degree, very few studies have attempted to isolate the effects of a parallel prototyping

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strategy on design outcome for physical prototypes experimentally since a parallel strategy can cost significantly more money and take more time to implement (Camburn, Arlitt, et al. 2017). Since physical prototypes provide designers with valuable information about the problem being solved during development (Kiriyama and Yamamoto 1998), there is a need to better understand how different prototyping strategies for physical prototypes affect design outcome. Tangible models have been shown to influence decision-making during the design process as a means for "exploration, verification, communication, and specification" (Verlinden and Horváth 2009).

Prior literature trends towards a parallel prototyping strategy having likely benefits for the design process in the context of software design, though parallel prototyping was not completely isolated from an iterative strategy. Dow et al. showed that a parallel prototyping strategy for the creation of internet advertisements yielded increased advertisement clicks, more divergent designs, and increased self-efficacy for student participants when compared to a purely iterative process (Dow et al. 2010; Dow et al. 2009a, b). However, extensive iteration was still present in the experimental design for the parallel prototyping conditions since participants received expert feedback on their parallel designs at multiple points during the study serially. Their research also reported on an "egg-drop" experiment as an investigation of the effects of parallel prototyping vs. iterative prototyping when designing physical prototypes; results were largely inconclusive since no differences were seen in performance between the iterative and parallel conditions (Dow et al. 2009a, b). This was likely because performance on the "egg-drop" problem was extremely sensitive to small deviations in construction of the dropped vessels, such as loose tape (Dow et al. 2009a, b). Based on the literature review presented in the background section, there is a need to understand how parallel prototyping affects the engineering design process when working with physical artifacts.

Parallel and iterative design strategies have also been studied in the context of industry (Fricke 1996) and articulated in seminal work on the design process as a beneficial strategy depending on cost and time constraints (Pahl and Beitz 2013; Ehrlenspiel et al. 2007). Much of the prior work on this topic primarily focuses on the implementation of the design process wtih consideration for company workflow and overall development efficiency and not necessarily the effects of different prototyping strategies at a lower level of abstraction more oriented towards conceptual design. Parallel prototyping likely has the most significant impact on designs where functionality of the design is not yet well understood. In this study, we chose a design problem where participants likely did not have extensive prior task experience. Many cases in industry match these conditions as indicated by the fact that design firms, like IDEO (Kelley 2001) and Dyson (Dyson and Coren 2001) tend to rely heavily on prototyping as a part of their processes because they design a wide variety of products. The results of the study presented in this article likely have strong implications for how designers should prototype in industry, especially in cases where existing engineering models that accurately represent the design are sparse and prior experience is low.

This article explores the differences between an iterative vs. parallel prototyping strategy for physical prototypes through a controlled experimental study in a mechanical engineering design context. This study was carefully developed to remove as much iteration as possible from the parallel condition. The participants were not provided with any expert feedback on their concepts throughout the study; they learned about their designs from their own testing. This allowed the results to be better attributed to novice learning and not the guidance of experts. In addition to competition performance, participants' engineering design self-efficacy (confidence, motivation, expectation of success, and anxiety) was measured before and after the design competition. A final survey was also collected to capture participants' overall design experience throughout the study. Through this research, the authors aimed (1) to understand differences in resulting design success between an iterative vs. parallel prototyping strategy, (2) to investigate changes in participants' engineering design self-efficacy as affected by prototyping approach, and (3) to measure the breadth of design space exploration through prototype similarity, based on the prescribed prototyping strategies.

The authors hypothesized that a parallel prototyping strategy would be correlated with better design success because participants would make more significant changes in their designs than with an iterative strategy, which would ultimately lead them to find better solutions (H1). Second, it was hypothesized that a parallel prototyping process would improve engineering design self-efficacy since participants might get more experience using different modeling operations if they chose to create two unique design solutions (H2). Finally, the authors hypothesized that a parallel strategy would encourage broader exploration of the solution space through prototypes that are less similar to each other since participants would not have an opportunity to iterate between their first and second prototypes (H3).

2 Background

This section provides an overview of published work on prototyping in engineering design. First, definitions of the term "prototype" are discussed followed by research on key prototyping considerations such as medium, expertise, and fidelity. Next, published prototyping strategies and categorization frameworks are reviewed. The background section finishes with a conversation on research specifically focused on parallel prototyping with identified gaps in the literature that ultimately motivate this work.

2.1 Prototyping in engineering design

Prototyping is a critical part of the engineering design process. Seminal texts describe prototypes as physical artifacts that allow designers to test various aspects of a design concept before sending a product to market (Otto and Wood 2001; Dieter and Schmidt 2009; Ullman 1992). Prototypes serve as a way for designers to communicate, learn, integrate systems, and reach milestones during a product development cycle (Ulrich and Eppinger 2015). Specifically, Ullman describes four different purposes for a prototype including proof-of-concept, proof-of-product, proof-of process, and proof-of-production (Ullman 1992). The discussion around prototyping almost always describes it as an iterative process (Dieter and Schmidt 2009; Camburn, Dunlap, et al. 2015; Dym and Little 1999; Pahl and Beitz 2013) often labeling different prototyping stages as alpha, beta, and preproduction (Otto and Wood 2001; Eggert 2005). Camburn et al. suggest that the embodiment of a prototyping iteration can be described by "the scale, the system level, the requirement fidelity, and the media" (Camburn, Viswanathan et al. 2017).

Work has also been done on classifying the purpose of a prototyping. By reviewing literature on prototyping, Petrakis et al. identified seven roles for a prototype: learning, communication, demonstration, integration, refinement, exploration, and requirement elicitation (Petrakis, Hird, and Wodehouse 2019). In a more recent publication with a revised list of prototyping roles, Petrakis et al. showed that engineering students "do not maximize the benefits of prototyping and require more explicit guidelines and encouragement" (Petrakis, Wodehouse, and Hird 2021). Their work investigated these effects for physical prototypes. An article focused on how novices utilize prototypes by Deininger et al. found similarly that novices showed engagement with prototyping best practices, but "they did so infrequently, mostly unintentionally, and without a structured approach" (Deininger et al. 2017). Exposing novices to structured prototyping approaches may help them appreciate the value of prototyping in engineering design, especially during the earlier stages of the design process.

There is some disagreement in this seminal work as to whether the term prototype exclusively pertains to physical models or pertains to both physical and virtual models. Dieter and Schmidt explicitly define "prototype" as "a physical model of the product, as opposed to a computer model (CAD model) of the product or other simulation of the design" (Dieter and Schmidt 2009). Others make similar claims as well (Otto and Wood 2001; Dym and Little 1999). In contrast, Ulrich and Eppinger present a broader definition of the term prototype that includes "concept sketches, mathematical models, simulations, test components, and fully functional preproduction versions of the product" (Ulrich and Eppinger 2015). The idea that prototypes can be either physical or virtual as opposed to only physical seems to be commonplace in published research articles (Christie et al. 2012; Wall et al. 1992; Dunlap et al. 2014; Camburn, Viswanathan et al. 2017). In the study presented in this article, computer models and physical models are both considered to produce prototypes in different forms as part of the prototyping process in engineering design.

Prototypes facilitate learning during the engineering design process (Ulrich and Eppinger 2015). Leifer and Steinert introduced three learning loops to describe conceptual change during the design process and describe how rapid prototyping iterations accelerate the rate of learning during design (Leifer and Steinert 2011). This idea is expanded on by the presentation of a framework that leverages these learning loops to describe the creation and transfer of knowledge through prototyping in an automotive context (Erichsen et al. 2016). We believe that engineering novices have greater potential for learning from prototyping activities than professional engineers because they have far less experience, especially in the domain we chose for the experiment. Research has shown that there is a difference between how students and experts engage with the design process, where experts spend significantly more time on gathering information and scoping the problem (Atman et al. 2007). Experts have also been shown to perform better than novices in unfamiliar domains (Adelson and Soloway 1985; Schraagen 1993). Further, engineering students have a narrower conception of prototyping than professional engineers, believing that prototypes are primarily used to test functionality (Lauff, Kotys-Schwartz, and Rentschler 2017). There is room to expand how the prototyping process is taught to novices beyond their use for testing functionality at specific stages during product development. Based on this published work, the study described in this article involves novice engineers as participants because they likely do not have a strong framework for engaging with engineering design and have more to learn than expert engineers from the prototyping process itself.

There is also a body of work that investigates how prototypes are used in terms of fidelity, where prototype fidelity refers to "the degree to which a model of the system resembles the target system" (Sauer et al. 2008). At either ends of the spectrum, a low-fidelity prototype could refer to a paper model and a high-fidelity prototype could refer to a beta-prototype that is almost identical to the final product. Low-fidelity prototypes tend to be implemented during earlier stages of the design process and are often function-focused (Jensen et al. 2017). Research has suggested that low-fidelity paper prototypes give comparable feedback on usability to high-fidelity designs (Walker, Takayama, and Landay 2002), but others warn that low-fidelity prototypes may exaggerate usability issues when compared to high-fidelity prototypes (Sauer et al. 2008). Further, high-fidelity prototypes have been shown to encourage correct and confident design decision-making where low-fidelity prototypes are more useful for examining product functionality (Hannah et al. 2012). From these results, a design problem requiring the production of high-fidelity, function-focused prototypes was chosen for the experimental study presented in this article because they likely promote learning and encourage confident decision-making.

2.2 Prototyping strategies and frameworks

An iterative approach to the prototyping process is the most commonly found strategy for successful design (Otto and Wood 2001; Dieter and Schmidt 2009; Ulrich and Eppinger 2015). Empirical studies show that multiple iterations improve design success even if those participants have less prior task experience than participants performing a single iteration with more task experience (Dow, Heddleston, and Klemmer 2009), show that early iteration can increase product quality and reduce project time (Osborne 1993), and show that structured iteration helps teams identify errors and meet requirements compared to a control condition with no prescribed strategy (Camburn et al. 2013). Buxton suggests that the idea of iteration is limited to the evolution of a single concept as opposed to considering multiple concepts simultaneously (Buxton 2010), where we call the simultaneous consideration of multiple concepts "parallel prototyping" in this article. The idea that iteration is central to the engineering design process is evident when examining frameworks such as the Design Sprint outlining a 5-day design structure (Knapp, Zeratsky, and Kowitz 2016), Lean Startup emphasizing testing and feedback (Ries 2011), and Agile Design suggesting functionality should be divided into smaller projects (Böhmer et al. 2017; Schuh, Doelle, and Schloesser 2018; Ullman 2019). All of these design strategies encourage an iterative process for rapid product development.

Researchers have made attempts to outline other specific prototyping strategies. Menold et al. created a strategy called "Prototype for X (PFX)" that provides a framework for prototyping activities and includes guiding documents for implementation (Menold et al. 2017, 2016, 2019). The Prototype for X framework, based on human-centered design (Boy 2012), helps engineering designers focus on critical design aspects through three phases: Frame, Build, and Test (Menold et al. 2017). Through empirical evidence, this strategy increases prototyping awareness (Menold et al. 2016) and increases design quality among student designers (Menold et al. 2019). From an extensive case study of a startup company's prototyping process, a visualization strategy for prototype documentation was created called a "ProtoMap" (Hansen and Özkil 2020). Though incredibly insightful for discovering patterns and trends in design activities, this strategy does not necessarily guide a designer's decisions while engaging in prototyping activities. As a final example, Thomke suggests appropriate application of prototyping technologies to reduce overall time and cost of design based on results from a questionnaire sent to 1000 designers (Thomke 1998). The paper claims that switching between modes of prototyping technology (i.e., mathematical models vs. foamboard mockups) at optimal moments in the design process can have positive effects on design outcomes (Thomke 1998). With this literature in mind, the new study presented in this article involves the effects both physical and virtual prototypes on design outcome.

Beyond prototyping strategies, researchers have also made attempts to create classification frameworks to describe the different types of prototypes used in engineering design. In an attempt to better classify prototypes in terms of knowledge acquisition, Erichsen et al. proposed a framework based off of a published model for organizational knowledge creation known as SECI (Socialization, Externalization, Combination, and Internalization) (Nonaka et al. 2000) that makes distinctions between prototypes that are external vs. internal and reflective vs. affirmative (Erichsen et al. 2016). This framework tries to capture the different types of avenues through which prototypes facilitate design learning. In another example, a new planning tool was created based on six identified prototyping heuristics: iterative, parallel, scaling, subsystem, requirement relaxation, and virtual prototyping (Camburn, Dunlap, et al. 2015; Dunlap et al. 2014). While these categories are insightful, it is not entirely clear how a designer should make decisions about them with little empirical evidence to support a specific strategy. Finally, Dahan and Mendelson describe four modes of prototyping called one-shot, sequential, parallel, and hybrid (Dahan and Mendelson 1998). Their work showed that parallel prototyping is likely most appropriate when production costs are lower and project times are shorter when compared to the other three modes explored (Dahan and Mendelson 1998). Considering this, the new experimental study presented in this article is a low-cost, time-constrained design scenario, which is appropriate for a parallel prototyping strategy.

Despite the existence of these strategies and frameworks, there is a surprising lack of research investigating the theoretical basis behind them. Moe et al. state that while "methods exist to elicit and systematically address requirements", prototyping strategies "tend to be more art than science, more pragmatic than grounded with theory" (Moe, Jensen, and Wood 2004). The new results from the study presented in this article aim to expand the theoretical basis for these structured prototyping approaches. Specifically, we aim to explore the effects of a parallel prototyping process on design success, self-efficacy, and solution space exploration compared to the more common iterative approach described in the literature.

2.3 Parallel prototyping

Research articles identify parallel prototyping as a key consideration when planning a product development cycle (Dunlap et al. 2014; Camburn, Viswanathan, et al. 2017). Parallel prototyping has links the popular idea of "concurrent engineering", where different stages in a product development cycle occur simultaneously (Birmingham and Ward 1995). To be clear, "concurrent engineering" is also called "simultaneous engineering" in the literature (Ehrlenspiel et al. 2007). Concurrent engineering shares similarity to the idea of parallel prototyping in that concurrent engineering is a parallel approach to design that encourages simultaneous development at different stages of the engineering design process (Prasad 1999). Similarly, parallel prototyping encourages simultaneous development of multiple concepts before selecting a final design.

There exists a body of literature that has primarily been concerned with parallel prototyping strategies. For example, an extensive case study of a startup company that tracked their prototyping activities showed that the introduction of parallel prototype concepts usually indicated radical changes in product development (Hansen and Özkil 2020). These parallel prototypes often represented isolated subsystems that helped broaden the solution space and were later integrated into a single design (Hansen and Özkil 2020). Empirical studies have also shown the benefits of a parallel prototyping process with some limitations. Camburn et al. showed that including parallel concepts during the prototyping process statistically increased performance on a design task and that exploration of a parallel concept began when a design team realized their first concept was not working well (Camburn, Dunlap, et al. 2015). However, participants were not required to parallel prototype explicitly and parallel prototyping activities were identified after completion of the study. Neeley et al. conducted a study that encouraged the creation of up to five multiple prototypes simultaneously, which they call "divergent prototyping" (Neeley Jr. et al. 2013). In Neeley et al.'s study, student participants that designed multiple concepts during a first iteration outperformed those that only produced one concept, though students that designed multiple concepts also reported that they felt time-constrained and were dissatisfied with their designs during the first iteration (Neeley Jr. et al. 2013). However, Neeley et al. point out in their paper that many participants in the experimental condition did not produce multiple designs despite the requirement (Neeley Jr. et al. 2013). Due to participants failing to produce multiple designs as instructed, it may be that the better designers tended to produce more ideas and results were not due to the conditions of the experiment. While this research is similar to the study presented in this article, one key difference is that all participants in the parallel condition of our study successfully produced multiple prototypes in parallel as required.

Dow et al. published work focused on parallel prototyping strategies that included both a physical and a virtual design problem (Dow et al. 2010; Dow et al. 2009a, b) and measured participants' self-efficacy before and after the design activities. The study involved an online advertisement (as the virtual design problem) and an "egg-drop" activity (as the physical design problem). Their results suggest that parallel prototyping led to better online advertisements, greater solution divergence, and improved self-efficacy (Dow et al. 2010), but results from the "egg-drop" activity were largely inconclusive (Dow et al. 2009a, b). The publications by Dow et al. most closely relate to the study presented in this article and reveal an opportunity to better understand how iterative and parallel prototyping strategies affect the engineering design process for physical prototypes since results were largely inconclusive for their physical prototyping activity. To the best of our knowledge, there are few published articles on the effects of parallel prototyping for physical artifacts, and those that exist report notable experimental limitations that make drawing theoretical conclusions difficult. The study presented in this article provides clear evidence of the advantages that come with a parallel prototyping strategy over an iterative strategy for physical products in the context of engineering design.

3 Methodology

As discussed in the background section, prototypes facilitate learning during the engineering design process. Novices with little prior knowledge of the design problem or experience implementing a prototyping strategy were selected as participants because they would likely have the most to learn, which would accentuate the effects of the two different prototyping strategies. Further, a design problem that required the creation of high-fidelity, function-focused prototypes was chosen because it allowed us to design a more controlled experiment than other published work on the topic. These decisions were made to highlight the effects of parallel prototyping, which could justify more costly implementation in an industry setting.

The methodology section provides details about the study context, experimental design and procedure, research materials, competition details, and prototype evaluation process. Data was collected as part of an in-class design competition project. The details of this competition are provided in Sect. 3.4 along with an outline of all tasks completed by the student participants. Accompanying documentation is provided in the Appendix.

3.1 Participants

This study was conducted in a first-year undergraduate mechanical engineering course at a research-focused public university in the southeastern United States. In this introductory course, students learn the basics of free-hand sketching, design principles, and computer-aided design. This study took place during the portion of the course on computer-aided design at the end of the semester for a total of 7 weeks. In total, 46 student participants voluntarily consented to the IRB approved study and completed all portions with 11 students self-reporting as female and 35 as male. Of these 46 students, 23 were randomly assigned to the iterative prototyping condition and 23 were randomly assigned to the parallel prototyping condition.

3.2 Experiment design

The research team took care to design an experiment that would isolate the effects of parallel and iterative prototyping from each other as much as possible. Student participants were divided into two conditions: the iterative condition and the parallel condition. The two experimental conditions followed different prototyping processes as shown in Fig. 1. Notice that both experimental conditions generated two prototypes and a single final prototype, which equally distributed the amount of work participants were required to do for the project. The parallel condition was not necessarily required to produce two unique concepts, though many did.

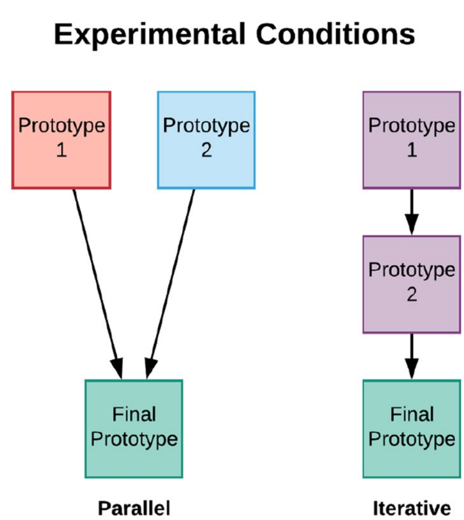

Fig. 1 Two experimental conditions (the parallel condition and the iterative condition) altered the participants' prototyping processes. The parallel condition modeled two concepts simultaneously while the iterative condition created models serially

This was communicated to the participants verbally during lecture, specifically noting that participants in the parallel condition did not have to produce two entirely unique prototypes but could if they thought it would help their design process. Notably, the two conditions were aware of the other because of constraints that were beyond the control of the research team. This could have had an effect on whether participants in the parallel condition chose to produce two unique or two conceptually similar designs, but this idea expanded on later in the article.

This framework (Fig. 1) guided the research team's selection of a design problem for this study. Ideally, participants would be removed from the actual production of the prototypes so that learning from the first two prototypes in the parallel condition would happen simultaneously and occur serially for the iterative condition. A design problem that involved additive manufacturing fit well within this constraint because participants could be restricted from producing the prototypes themselves. This was critical to the experimental design because the research team was better able to control how many design iterations occurred and kept the parallel condition devoid of as much iteration as possible. It is easy to imagine the participants creating more prototypes than required while working on this project to create final prototypes that would be more successful in the final competition, which could compromise the premise that participants in the parallel condition were actually solely using a parallel prototyping strategy.

While engineers and designers often build prototypes themselves as a hands-on experience, this experimental study was primarily concerned with isolating the different theoretical prototyping strategies and not the effects that physically constructing a prototype has on design success. Allowing the participants to physically manufacture the prototypes themselves would have introduced unwanted noise into the study that would have made the results more difficult to attribute to the prototyping strategy itself.

With this in mind, participants were tasked with creating a device to launch a small foam ball into a target of plastic cups at variable distances, as shown in Fig. 2. The design problem was carefully chosen to allow for solution diversity within the constraints of 3D printing technology and to provide quantitative results as an indication of design success. Throughout their prototyping process, participants did not receive any expert feedback about their designs unless they had a misunderstanding about the limitations of 3D printing, since this was conducted in an introductory course. No feedback about the quality, feasibility, novelty, etc. of their designs was provided to the participants from the research team, teaching assistants, or the course instructor so that design changes could be attributed to student learning from their returned prototypes and not expert advice or opinion. More details about the design competition and

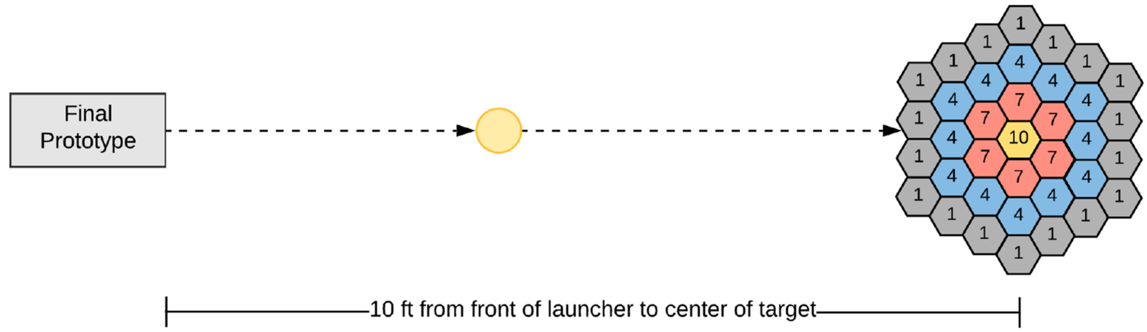

Fig. 2 Depiction of competition setup with more points for the center of the target (10 points) and less at the edge of target (1 point) as indicated

design problem can be found in Sect. 3.4 including material descriptions and scoring methods of the final competition.

This study required data collection at many points during the 7 weeks of this student project; they are enumerated below in chronological order below. Note that for the parallel condition, Prototype 1 and Prototype 2 were submitted and returned simultaneously whereas for the iterative condition, Prototype 1 and Prototype 2 were submitted and returned in sequence. Participants took their prototypes home and tested their designs on their own with materials provided to them that were identical to the materials used in the final competition. After they tested their prototypes, participants made changes to their designs for the final competition as a final step (parallel condition) or as an iterative process before the second and final prototypes (iterative condition). Final prototypes were submitted at the same time for both experimental conditions.

3.2.1 Experimental procedure

1. Consent and demographic survey
2. Self-efficacy survey (pre-prototyping)
3. Prototypes 1 and 2 (either simultaneously or sequentially)
4. Final prototype
5. Ball-launching competition
6. Self-efficacy survey (post-prototyping)
7. Post-prototyping survey
8. Project report

After participants competed in the final competition, Prototype 1, Prototype 2, and the Final Prototype were collected for further analysis by the research team. Participants could have their prototypes returned to them upon request after documentation and analysis.

4 Research materials

As part of this study, a brief demographic survey was completed first by student participants. In addition, engineering design self-efficacy (EDSE) was measured using a survey created, validated, and published by Carberry et al. (Carberry et al. 2010), which is widely used in engineering design research (Hilton et al. 2020a; Gerber, Marie Olson, and Komarek 2012; Telenko et al. 2014; Genco, Hölttä-Otto, and Seepersad 2012). Participants completed the EDSE survey at the beginning and end of the study. Notice that Dow et al. also measured self-efficacy, but used a measurement adapted from education research (Dow et al. 2010). In contrast, the study presented in this article utilizes a self-efficacy survey specifically focused on the engineering design process. Results from this work are compared to results found by Dow et al. in the discussion section.

Student participants created computer-aided design models of their prototypes using Solidworks, a standard 3D modeling software commonly taught in mechanical engineering curricula. These models were submitted electronically to the research team that then took them to a 3rd party 3D printing service to have them produced using a material deposition method on FlashForge Creator Pro machines with a standard grey polyactic acid (PLA). These prototypes were all printed with a 300-micron layer height resolution and 15% infill. This resulted in 138 total 3D-printed prototypes that were returned to the participants during the design process and later collected for further analysis after the final competition.

Finally, a brief post-prototyping survey was created by the research team to measure participants' experience with the design project and their satisfaction with their prototyping condition after the entire experience. Since this survey was created for the purposes of this study specifically, questions were asked multiple times in different ways to eliminate any unintentional biases. Responses to this survey reveal participants' perception about how their prototyping condition impacted their design process. This survey can be found in the Appendix.

4.1 Competition details

Participants were tasked with designing a rubber band powered device to launch a foam ball into a target made of plastic cups 10 feet away measured from the front of their device to the center of the target. Their prototypes and final design had to fit within a 4″ deep, 5″ wide, 4″ tall build volume. Their prototypes could have as many or as few parts as they wanted as long as they could be arranged to fit inside of this constraint to ensure total print times were manageable. In addition, their device had to have two stable states—such as a "primed" and a "launched" position—to deter participants from creating rudimentary slingshots. Their devices also had to operate from ground level. Participants were not allowed to use any outside materials such as glue, tape, paperclips, etc. to help control the solution space, and were not allowed to print their own prototypes at home or in the university makerspace for reasons already discussed. During the competition, they could launch the foam balls up to five times keeping their top three scores. Their final score was comprised of a *distance score* and a *raw score* summed together for each attempt to earn a *competition score*. A graphic that shows the competition setup is shown in Fig. 2.

Standard size 33 rubber bands were provided to participants. The small foam balls were 2.3 cm in diameter; they could ask for more as needed while testing their prototypes before the competition. For the target, 16 oz capacity drinking cups with a unique hexagonal design were taped together and filled with colored beads to help indicate earned points and stabilize the cups. Points were also awarded depending on how close the final prototype was to the ideal 10 feet design requirement called their *distance score*. These points were awarded as shown below (Table 1).

Table 1 Different amounts of points were awarded for launch distance depending how closely participants met the 10 feet design requirement, called the distance score

Additional points	Distance from target	
	Too close	Too far
10 pts	9.5 ft to 10.5 ft	9.5 ft to 10.5 ft
7 pts	8.5 ft to 9.5 ft	10.5 ft to 11.5 ft
4 pts	7.5 ft to 8.5 ft	11.5 ft to 12.5 ft
1 pts	6.5 ft to 7.5 ft	12.5 ft to 13.5 ft
0 pts	< 6.5 ft	> 13.5 ft

4.2 Prototype evaluation

After the competition was complete, all prototypes were collected for further analysis. A graduate research assistant conducting research in the area of engineering design, a graduate student studying industrial design, and a faculty expert in the field of design theory and methodology scored these prototypes for similarity. A 5-point scale was used from "Very Different" (5) to "Very Similar" (1). Scorers were instructed to define similarity as how they felt best fit the entire set of physical prototypes since this process was already qualitative in nature. Prescribing exhaustive dimensions of similarity such as form, structure, mechanism, aesthetics, etc. would have taken up a considerable amount of time and would not have allowed for categories to form naturally during examination. The scorers were not instructed to rate similarity based on functionality or apparent features to avoid biasing the results and to allow for their expertise to be the final determining factor in their ratings. Prototypes could have instead been scored for similarity by the raters in terms of functionality, feature similarity, or fidelity, but this did not specifically address the research questions of this study. Despite these seemingly unspecific instructions, this decision is supported by high inter-rater reliability between the similarity scorers as described in the results section. After data analysis, it appeared as though the scorers gave ratings largely based on apparent functionality. This might suggest a relationship between these different dimensions (functionality, apparent features, structure, form, etc.) of similarity, but is ultimately beyond the scope of this work.

During this process, scorers were blind to whether a group of prototypes were from the iterative condition or the parallel condition. Each expert performed four rounds of similarity scoring for each participants' prototypes: Prototype 1 to Prototype 2, Prototype 2 to Final Prototype, Final Prototype to Prototype 1, and all three prototypes in general (as a measure of design space exploration). The scorers would consider a participants' prototypes during each of the four rounds of scoring and assign a value from 1 to 5 until all prototypes had been scored for each round of scoring.

5 Results

Competition performance, changes in pre- and post-engineering design self-efficacy (EDSE), similarity scoring of the physical prototypes, and post-prototyping survey responses are all reported in the following subsection. In-depth interpretations of these results are reserved for the discussion section.

5.1 Competition performance

The design problem was clearly challenging for the participants. This is the type of situation where parallel prototypes likely have the greatest impact on the design process because there are ample opportunities for learning. Only 12 participants of 26 actually scoring any points at all; most of the participants' devices were unfortunately not reliable enough to get the foam ball into the cup even with 5 attempts. However, of the 12 that scored points, 9 were in the parallel condition with an average score of 14.22 points and 3 were in the iterative condition with an average score of 9.00 points. This difference was statistically significant through analysis with a Chi-squared test $\chi^2(1, n=46)=4.059$, $p=0.044$, which indicates that the participants in the parallel condition were more likely to design devices that would score points in the competition.

5.2 Engineering design self-efficacy

Participants' engineering design self-efficacy from before the start of the study to after the design competition was compared between the two experimental conditions. Shown in Fig. 3, these self-efficacy results are divided by the iterative condition and parallel condition, as well as by pre- and post- scores with error bars of +/− 1 standard error.

Figure 3 indicates that the parallel condition shows increased confidence and reduced anxiety when conducting engineering design. These results are statistically significant through paired two-sample t tests for confidence ($t(22)=-3.201$, $p=0.004$) and for anxiety ($t(22)=3.246$, $p=0.004$); data were checked for normality and adequately meet the assumption. No significance was found between the pre- and post-EDSE scores across the four dimensions for the iterative condition, and no significant differences

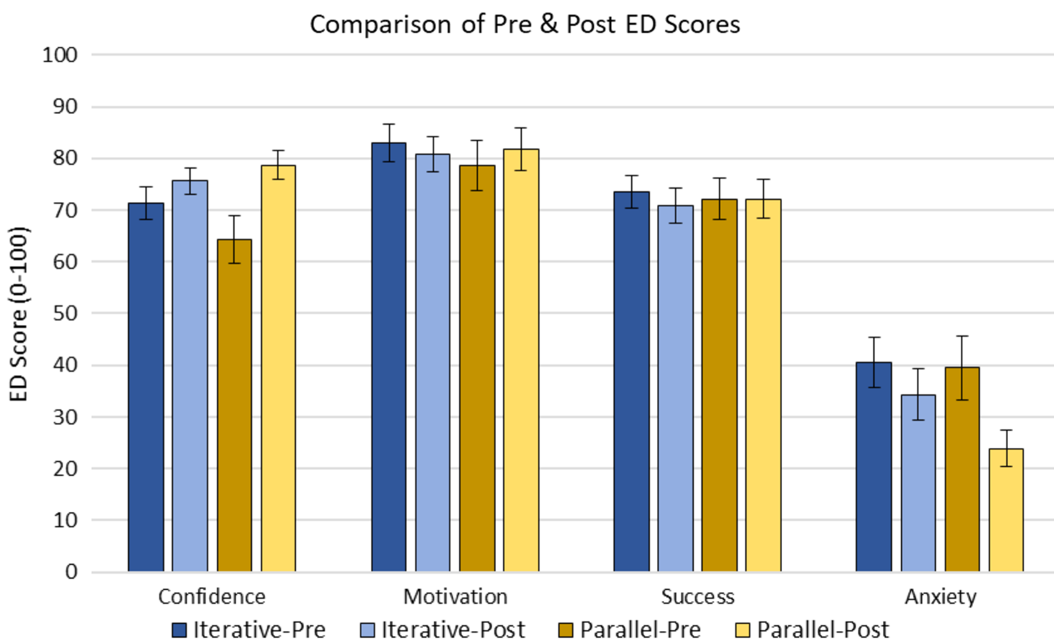

Fig. 3 Average Engineering Design Self Efficacy (EDSE) scores between the iterative condition and parallel condition during the pre- and post-data collection with error bars of +/− 1 standard error

Table 2 This shows average similarity scores with p values for condition comparison that show significant differences between the two experimental conditions (1 = Very Similar, 5 = Very Different)

Condition	Comparison	df	Mean Similarity	t stat	p value
Iterative	Prototype 1 and Prototype 2	44	1.57	−4.108	< 0.01
Parallel	Prototype 1 and Prototype 2	44	3.43		
Iterative	All 3 Prototypes	44	1.74	−3.989	< 0.01
Parallel	All 3 Prototypes	44	3.43		

were found between the iterative condition and the parallel condition in the pre-prototyping or post-prototyping EDSE scores for each category. Interpretations of why these significance differences occurred while others did not are elaborated upon in the discussion section.

5.3 Similarity scoring of physical prototypes

Results indicate that prototypes from the parallel condition are less similar to each other than prototypes from the iterative condition. As previously stated, three experts scored the physical prototypes for similarity. Table 2 shows a significant difference between the iterative condition and the parallel condition when considering prototype similarity between Prototype 1 to Prototype 2 and among all three prototypes in general using two-sample *t* tests between the two experimental conditions. Only one scorer's results are reported because all scorers had similar results, which are described below with inter-rater analysis. There is clearly a significant difference between the iterative and parallel condition in terms of prototype similarity.

These results indicate that the parallel condition produced prototypes that were less similar to each other considering Prototype 1 and Prototype 2, as well as considering all three prototypes in general. To ensure that these results were reliable, Pearson's Correlations were calculated between each pairing of scorers. Table 3 shows the correlation values between the scorers and indicate good agreement between the scorers on prototype similarity.

The values obtained from an analysis using Pearson's Correlation indicate good agreement between the scorers on prototype similarity. Finally, intraclass correlation was calculated between the iterative condition and parallel condition for similarity scores on Prototype 1 vs. Prototype 2 and for all three prototypes as a set. For similarity scores on Prototype 1 vs. Prototype 2, intraclass correlation analysis gave a value of 0.740 indicating good correlation. For similarity scores among all three prototypes, intraclass correlation analysis gave a value of 0.799 indicating excellent correlation. Taken together, values obtained for Pearson's Correlation and intraclass correlation show that the scores for prototype similarity are reliable between the raters and confirms the decision to allow scorers to rate similarity based on their own intuition.

Table 3 These collected values for Pearson's Correlation indicate good agreement between different pairings of raters on the similarity of the prototypes

Pairings	Pearson's Correlations	
	Prototype 1 vs. Prototype 2	All 3 Prototypes
Scorer 1 to Scorer 2	0.869	0.783
Scorer 2 to Scorer 3	0.729	0.758
Scorer 3 to Score 1	0.796	0.719

Note: All *p* values are less than 0.001

5.4 Post-prototyping survey

After completing the competition, student participants filled out the post-prototyping survey indicating how much they agreed or disagreed to various statements on a 5-point Likert scale (Appendix). Responses were divided by experimental condition for further analysis and interpretation. Results from the survey are shown in Fig. 4 with error bars of +/− 1 standard error.

The largest differences in response were on Questions 3, 4, and 7. Question 3 stated "*I was satisfied with my random group assignment (iterative vs. parallel)*" where participants in the iterative condition self-reported as much more satisfied with their random assignment than participants in the parallel condition with statistical significance ($t(44) = -5.814$, $p = < 0.001$). Question 4 stated "*My group assignment positively affected my design process*" where participants in the iterative condition believed that their random assignment positively affected their design process with statistical significance ($t(44) = -3.159$, $p = 0.003$) despite a generally worse performance in the design competition than the parallel condition. Finally, Question 7 stated "*I would have rather been assigned to the opposite prototyping group (iterative vs. parallel)*" where participants in the parallel condition showed a strong preference to switch conditions with statistical significance ($t(44) = 6.419$, $p = < 0.001$) compared to the iterative condition, again despite better performance in the competition. Responses were not statistically different on Question 6 ("*There was enough time for me to complete all of the prototype submissions by the assigned due dates*") or on Question 11 ("*I had all of the resources I needed to perform well in the design competition*"), which suggests that this difference in strategy preference cannot easily be attributed to a disparity in the amount of work or time participants had to complete their prototypes depending on their condition assignment. Causes for these differences in response are explored in detail in the following discussion section.

6 Discussion

The following subsections describe interpretations of these results in roughly the same order as they are presented for convenience and concision. Interpretations of competition performance, engineering design self-efficacy differences, solution space exploration, and participants' perception of prototyping processes are included.

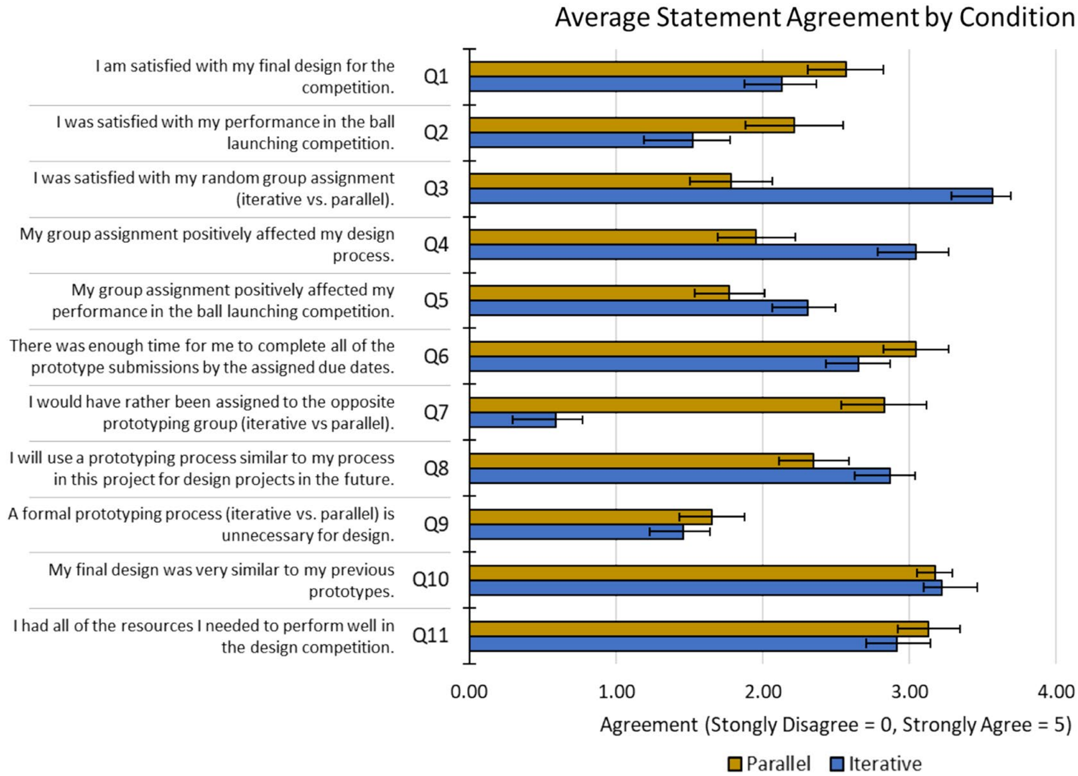

Fig. 4 Average agreement to statements on the post-prototyping survey completed after the design competition with error bars of ± 1 standard error

6.1 Design competition performance

Participants in the parallel condition outperformed the iterative condition with statistical significance, which supports the authors' first hypothesis (H1) that "a parallel prototyping strategy would be correlated with better design success". One possible interpretation of this result might be that participants in the parallel condition often elected to model two drastically different concepts during the prototyping phase and therefore gained greater experience using the modeling software. Another possible interpretation is that parallel prototyping allows exploration of different functional solutions that are ultimately synthesized into a single final design. Further, based on results from other measures in this study, it is clear that participants in the parallel condition explored more of the solution space for this design problem.

6.2 Changes in self-efficacy

Participants in the parallel condition showed increased confidence and reduced anxiety for conducting engineering design, whereas no changes were found for the iterative condition. Though the authors' expected increases in self-efficacy across all four dimensions measures by the EDSE tool, the second hypothesis (H2) that states "a parallel prototyping process would improve engineering design self-efficacy" is partially supported by these results.

Upon reflection, improvements in EDSE motivation or success are not expected since performance in the design competition was so poor. Since most participants were unsuccessful in the competition, the lack of change in EDSE Success for both conditions makes sense. Since all parts were printed by the research team and not by the participants themselves, it is also not surprising that no changes are shown for EDSE motivation. changes in motivation have been positively correlated to makerspace involvement in the literature (Hilton et al. 2020b), where participants get hands-on experience making prototypes. In this study, participants did not get this hands-on design experience, so the absence of change in EDSE motivation is not surprising.

Increased confidence could be attributed to participants in the parallel condition often modeling two unique design concepts as opposed to one concept iteratively. This would likely improve their confidence using computer-aided design tools and conducting engineering design with the added experience from working on two different concepts. In contrast, participants in the iterative condition typically did not change concepts throughout the prototyping process. This same rationale can be applied to the reduced EDSE anxiety in the parallel condition. The prototyping process may have inherently encouraged participants to spend more time with the modeling software, which might reduce their anxiety about using computer-aided design tools and engaging in design more generally in the future. Participants in the parallel condition that prototyped two unique concepts also had more opportunities to learn about the limitations of parts manufactured through a material extrusion process and the limitations of translation from software model to a physically realized product. In other words, the reduced EDSE anxiety might be related to the greater learning opportunity afforded by a parallel prototyping process.

Whereas previous research showed inconclusive results about self-efficacy improvements during parallel prototyping of physical products (Dow et al. 2009a, b), the results presented here clearly show a significant difference in self-efficacy depending on prototyping strategy. The research team interprets these results in terms of opportunities for learning by the participants. Participants in the parallel condition had more opportunities to learn about the design problem and the solution space because many of them elected to design two different concepts during the initial prototyping phase of the project. This provided them with a greater opportunity for learning than was available to the iterative prototyping process prescribed to the other condition. This result is even more meaningful considering that participants were not required to design two different concepts and were explicitly told they did not have to, but rather many elected to do so simply because of the prototyping strategy's structure. In addition, recall that both conditions were required to produce two prototypes and final design under similar and comparable time constraints. With this in mind, it is clear that the parallel prototyping strategy inherently encouraged greater exploration of the solution space.

6.3 Solution space exploration through similarity

The previous two subsections have mentioned that participants in the parallel condition explored a greater region of the solution space than participants in the iterative condition. This interpretation is corroborated by results from the similarity scoring. Participants' designs in the parallel condition were less similar to each other than participants' designs in the iterative condition. This translates to greater exploration of the solution space and therefore better final designs, which supports the third hypothesis (H3) that states "a parallel strategy would encourage a broader exploration of the solution space through prototypes that are less similar to each other". A theoretical depiction of solution space exploration by the two experimental conditions is shown in Fig. 5.

This is one of many possible depictions of solution space exploration based on the results presented in this article, but this version combines all of the available data into an average representation of the prototyping processes taken by participants in the two different conditions (Fig. 5). It is not meant to reflect the quantitative data, but rather provides a visual representation of the results from the study. One notable alternative is that some solutions would actually fall outside of the bounds of the solution space and slowly converge towards the most feasible solution at the center. As shown, the distance from a final prototype from the parallel condition to the center is less than the distance from a final prototype in the iterative condition to the center, where the center is a theoretically most feasible solution. Results from the similarity scoring confirm that a parallel prototyping process encourages broader exploration of a design problem, which might lead to more creative, novel, and diverse designs while providing greater opportunities for learning from the prototyping strategy itself.

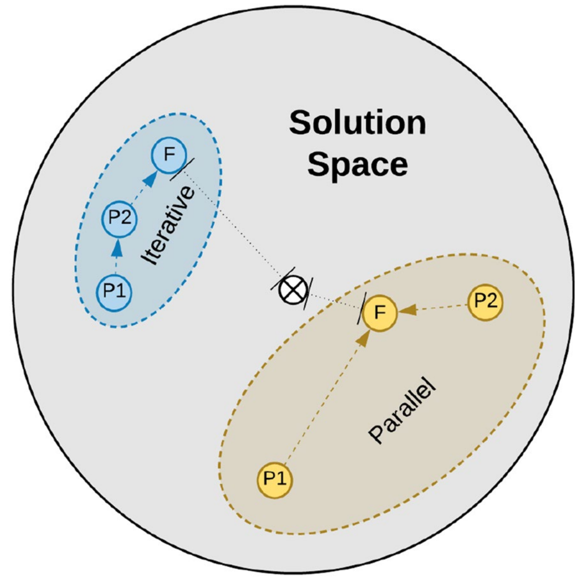

Fig. 5 This theoretical depiction of solution space exploration by the two experimental conditions shows greater solution space exploration by participants in the parallel condition. The center of the circle marks the theoretically most feasible solution, "P1" and "P2" indicate the first and second prototype respectively, and "F" indicates the Final Prototype

6.4 Perceptions of prototyping strategies

So far, a theoretical explanation with empirical evidence has been provided for the benefits of a parallel prototyping process in engineering design of physical products. Yet, there is a final surprising result that generates many more interesting research questions moving forward. Based on the post-prototyping survey, participants in the parallel condition were largely unaware of the benefits despite better competition performance, increased EDSE confidence, decreased EDSE anxiety, and more diverse exploration of the solution space. Every aspect of this study shows support for a parallel prototyping process, yet participants in the parallel condition would have rather been in the iterative condition. Further, participants in the iterative condition believe that the prototyping process more positively impacted their overall design process than participants in the parallel condition with significance. Given the clear support for a parallel prototyping process, this result was very unexpected.

This cannot be easily explained by participant perception of time and effort. At first glance, it might seem that participants in the parallel condition felt like a parallel prototyping process required more effort and time than an iterative process. However, results on the post-prototyping survey do not support this. As previously mentioned, Question 6 and Question 11 show that participants from both conditions felt similarly about the amount of time and the availability of resources they had to complete the project. One possible explanation for this unexpected result might be that iterative processes are engrained in our everyday lives, which translates to our prototyping preferences as engineering designers. A parallel prototyping strategy might require more cognitive effort than iterative prototyping because an engineering designer must consider multiple concepts simultaneously as opposed to a more linear trial and error process afforded by a purely iterative strategy.

It is likely that parallel prototyping is most beneficial earlier in the design process for design space exploration, stakeholder feedback, and concept formulation before moving towards an iterative strategy for refinement. Some work has been done in the context of product management (Thomke 1998) and instances of parallel prototyping has been shown to correlate with radical design changes (Hansen and Özkil 2020), but identifying when exactly this shift should occur is yet to be fully understood. However, these interpretations are not directly supported by the results of this study and further exploration of these ideas is left for future work. A portion of this exploration has been completed and published, where preliminary results indicate that an iterative approach to prototyping is perceived as associated with incremental adjustment and improvement whereas a parallel approach is perceived as associated with solution space exploration (Murphy et al. 2021).

6.5 Contributions and limitations

Compared to results by Dow et al. (Dow et al. 2010) that showed improvements in design success in a digital context, this study showcases how these ideas apply in an engineering design context with physical designs. While Dow et al. also reports on a design problem in a physical context (Dow et al. 2009a, b), they did not find significance in design success between the iterative and parallel strategies because the task was not sensitive to small variations in design implementation as reported by Dow, et al. (2009a, b). However, the results found in the current paper do indeed show significant differences in success during the final design competition between the two prototyping strategies. In the current study, self-efficacy was measured using a tool widely used in engineering design research and was shown to increase for participants in the parallel condition, which is consistent with results found by Dow et al. (2010) using a different but similarly appropriate measure.

Camburn et al. wrote that in future research “it would also be of value to experimentally validate marginal effects of parallel prototyping and the remaining techniques” (Camburn, Dunlap, et al. 2015). The work presented in this article experimentally validates some of those marginal effects. The results also indicate a novice preference towards iteration, which advances results shown by Deininger et al. that described that novices take an unstructured approach to the design process (Deininger et al. 2017). This article presents preliminary possibilities for why novices might resist alternative strategies for prototyping, such as the cognitive effort required for holding multiple concepts simultaneously in the mind. Future work is planned to investigate and articulate exactly why this preference exists and how to change it. Taken as a whole, this research has shown that a parallel prototyping strategy is equally as effective for physical prototyping as it is for digital prototyping and has significant advantages over the more traditional iterative approach, though students are largely unaware of these benefits.

A limitation of this study is that the two experimental conditions were aware of each other because of the constraints involved with implementing a seven-week study in an introductory engineering course. Future implementations of this experimental design could keep the two conditions blind to the existence of the other, which might reduce potential bias during the prototyping process, but participants clearly believe the iterative condition to be more effective, which contrasts with the results. Another limitation of this study is that the design problem may have been too difficult for first-year engineering undergraduate participants since very few of them scored any points at all in the design competition. This design problem might be more appropriate for upper-level undergraduate engineering participants that have more experience. Further, this study did not control for prior knowledge of computer-aided design or prior experience designing similar systems. Though assumed that the participants in this study were novices, some might have had exposure to modeling software that could have impacted their ability to realize their design ideas, whereas more limited knowledge could be a barrier to the prototyping process in general. Lastly, the results of this study might be specific to the design scenario. Utilizing additive manufacturing technology to produce the prototypes helped the research team control opportunities for learning and the pace of participants’ prototyping process. Other design problems or embodiment methodologies might yield different results.

7 Conclusion

This study has shown the benefits of a parallel prototyping strategy when compared to an iterative prototyping strategy. First, participants using a parallel prototyping strategy outperformed participants using an iterative prototyping strategy in a design competition. Next, those in the parallel condition showed increased design confidence and reduced anxiety for doing design tasks using a widely accepted measure of engineering design self-efficacy (Carberry et al. 2010). Finally, a parallel prototyping strategy encouraged greater exploration of the solution space. Taken together, these results provide evidence for the advantages of a parallel prototyping strategy in engineering design.

It is important to note that a parallel prototyping process will almost always inherently involve iteration. At the very least, there will almost always be a single round of iteration as designers select a single concept to further pursue. The experimental design of this study attempted to remove as much iteration from the parallel condition as possible to isolate its effects on design outcome. Removing the single round of iteration would have jeopardized the learning objectives established for the course, introduced unfairness as perceived by the student participants, and could have had a strong negative affect on success in the design competition. This is not to argue that the parallel prototyping strategy described in this article should be directly implemented when conducting engineering design, as it is restrictive. Instead, a combination of iterative and parallel approaches likely yields that best design outcomes. Before we can develop new approaches to the prototyping process, it is important to first understand the mechanisms behind existing approaches from a theoretical perspective. For the study presented in this article, the results suggest that the experimental design successfully isolated the effects and that this approach can be used for future studies on different prototyping strategies in engineering design.

As an additional result from this study, participants seem largely unaware of these benefits based on a post-prototyping survey where the parallel condition was less satisfied with their prototyping strategy assignment and the iterative condition felt more strongly that their prescribed prototyping process positively affected their final design. Yet, both conditions reported similar feelings about the amount of time and resources they had to complete the project. This result might indicate an engrained preference for iterative processes in general but requires further investigation and is left for future work.

A possible avenue for future work would be to implement this experimental design in its entirety in an upper-level undergraduate engineering course where more participants would be expected to perform more successfully in the design competition. This would allow for statistical analysis of actual competition score rather than analysis of binary success; the analysis in this article only considers whether participants hit the target or not. In line with the work by Deininger et al., it could be experimentally validated that students at the end of the undergraduate degree engage in structured and intentional prototyping practices (Deininger et al. 2017). It would also be interesting to introduce a time component into the study, which would allow the research team to investigate whether participants in the parallel condition spent more time and effort during the study than the iterative condition. This is valuable because it would describe whether the advantages of parallel prototyping shown in this study are worth it in an industry context. If the amount of time is comparable, a parallel prototyping strategy could more easily be adopted by engineering industry.

Another possible expansion of this work would involve collection and analysis of participants' CAD models. In this study, prototypes were defined as the physical models, but the CAD models could also be considered a type of prototype as indicated in the literature review. Results could be related back to course objectives and measured against modeling proficiency. As a final avenue for future work, there may be a relationship between different dimensions of similarity for physical prototypes (such as functionality, features, or fidelity) as evidenced by the high inter-rater reliability by the expert similarity scorers. Recall that these scorers were not given specifics as to what aspects of similarity were to be scored. Future studies that specifically address the relationships between different dimensions of similarity could be valuable to the field of engineering design research and could lead to new research methodologies.

The results from this study address the overall aims of this research. First, results have shown that a parallel prototyping strategy improves design success through measured performance in a design competition. Second, a parallel prototyping strategy increased confidence and reduced anxiety in the context of novice engineering design practice. And third, a parallel prototyping strategy yielded broader solution space exploration when compared to an iterative strategy. With this in mind, all three hypotheses were supported. A parallel prototyping strategy is correlated with greater design success, increased confidence and reduced anxiety during novice engineering design practice, and broader exploration of the solution space for the design problem.

Parallel prototyping strategies have proven benefits to the design process through its structure that requires exploration of multiple design concepts. The results of this study have implications beyond engineering education despite participants consisting solely of undergraduate engineering students. In particular, the broader exploration of solution space afforded by a parallel prototyping approach increases the likelihood that a designer will find a more optimized, cost-effective, and feasible solution in any design context including industry settings. Ultimately, a parallel prototyping strategy could save valuable time and money by allowing engineering designers to identify feasible and novel solutions earlier in the engineering design process and create more successful and unique products or services. Prototyping is a critical part of the design process and understanding how different prototyping strategies affect design outcome adds value to both engineering education and industry approaches to engineering design.

Appendix

Project outline given to students

3D-printed part project

Learning objectives

- Practice design process, moving from sketched concept to a 3D printed part
- Understand tolerances and differences between designed parts and physical parts
- Apply design for manufacturing considerations including the limitations of common FDM (fused deposition modeling) 3D printer to guide the printing process
- Articulate design for manufacturing considerations, choices, and justifications

Goal: Design a small object that can launch a ball, powered by a rubber band, into a target for a competition.

Project requirements

1. This project is an individual project, not a team project.
2. Size: Volume constrained to a spatial envelope no larger than of 4 in. × 5 in. × 4 in.
   a. 4" deep, 5" wide, 4" tall
3. Quantity: Everyone will print 2 prototypes + 1 final design for 3 total prototypes.
   a. There is no limit on quantity of parts for your prototype, as long as they can all fit together within the volume constraints at the same time during printing.
4. Prototypes should take as little time as necessary to print. This can be achieved by removing unnecessary material, minimizing support material, and designing within the volume constraints. Your professor and the TA's will help ensure that your parts will take a reasonable amount of time to print by looking at your models in lab as you work on your projects. This is important so that we can get everyone's prototypes printed in time to get them to you.
5. You must have at least four of the following CAD operations to create the part and it must have at least one interlocking feature.
   a. Extrusion (either extruded or extruded cut)
   b. Loft (either loft or loft cut)
   c. Revolve (or revolve cut)
   d. Spline
   e. Sweep (sweep or sweep cut)
   f. Mirrored portions or patterned
   g. Fillets or chamfers
   h. Text
6. Prototype must be complicated enough to justify 3D printing in place of building/prototyping using other processes (example, a block with a single hole, which can be more easily made with a table saw and drill press)
7. Prototype must be designed with good design for 3D printing practices such as:
   a. Minimized material usage
   b. Minimized support material, no trapped/inaccessible support material
   c. Proper use of over hangs, if applicable (see lectures)
   d. Design of appropriately sized features (see lectures)
8. You must use the provided rubber bands as elastic material and must design for the provided foam balls. You will be given these materials to test your prototypes with.
9. Your design must have "2 stable states". This means that you should be able to load the foam ball into your prototype, set the prototype to a "loaded" state, and then manipulate some part of your launcher to launch the ball. These two stable states will likely be a "loaded" state and a "launched" state.
10. You CANNOT use other materials in your prototype. All components must be 3D printed and assembled without the use of any adhesives, fasteners, tape, etc.
11. All 3D printed prototypes will be printed for you and returned to you in class. You are NOT allowed to print your own prototypes (i.e. in the invention studio). This is to ensure fairness to all students. Please do not help

each other or share insights with other students (since those who gave written consent will have their prototypes and reflections used for research purposes, it is very important that you do your own work on this project and honor these requests).

Competition outline given to students

Competition details

1. This design competition will be held during class on November 6th. You are to design a foam ball launcher, powered by a provided rubber band, to land in a target.
2. You are designing for a target 10 ft away as shown. This will be measured from the front of your launcher to the center of the target. You are allowed to move closer or further away from the target as you see fit, but this will hurt your final competition score. Details about scoring are below.
3. During the competition, you are allowed to exchange your rubber band once if you feel like there is something defective with the one you are provided. This is to ensure fairness.
4. Your design must rest on the ground during each ball launch.
5. You will launch five foam balls, one at a time, towards the target and your best 3 scores will be kept to calculate your competition score.
5. Students with the highest 3 “competition score” will receive 10 extra credit points on their final homework grade. The scoring details follow:

   a. Your top 3 scores of 5 will be summed for your "raw score".
   b. Cups closer to the center are worth more points as shown (i.e. 10 pts, 7 pts, 4 pts, 1 pts).
   c. Additional points are awarded based on your distance from the target. You are only awarded this “distance score” once, not for each launch.
   d. Your "distance score" will be added to your "raw score" for your total "competition score".
   e. If your "raw scores" were launched from different distances, the lowest "distance score" of your top three launches will be used.
   f. Maximum possible score of 40 points.

Post-prototyping survey

Post-prototyping survey

Name: ________________Group (Circle One): (Iterative) or (Parallel).

The following statements concern your experience with the ME 1770 individual project during the Fall 2019 semester. Please read each statement carefully. We are interested in your feelings, good and bad, about this individual project.

How strongly do you AGREE or DISAGREE with each of the following statements? (Circle One Number on Each Line).

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Don’t know
1.I am satisfied with my final design for the competition	1	2	3	4	5	0
2.I was satisfied with my performance in the ball launching competition	1	2	3	4	5	0
3.I was satisfied with my random group assignment (iterative vs. parallel)	1	2	3	4	5	0
4.My group assignment positively affected my design process	1	2	3	4	5	0
5.My group assignment positively affected my performance in the ball launching competition	1	2	3	4	5	0
6.There was enough time for me to complete all of the prototype submissions by the assigned due dates	1	2	3	4	5	0
7.I would have rather been assigned to the opposite prototyping group (iterative vs. parallel)	1	2	3	4	5	0
8.I will use a prototyping process similar to my process in this project for design projects in the future	1	2	3	4	5	0
9.A formal prototyping process (iterative vs. parallel) is unnecessary for design	1	2	3	4	5	0
10.My final design was very similar to my previous prototypes	1	2	3	4	5	0
11.I had all of the resources I needed to perform well in the design competition	1	2	3	4	5	0

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