Novice designers' use of prototypes in engineering design

Michael Deininger, Shanna R. Daly, Kathleen H. Sienko and *Jennifer C. Lee*, University of Michigan, George G. Brown Laboratory, Hayward Street, Ann Arbor, MI 48109, USA

Prototypes are essential tools in product design processes, but are often underutilized by novice designers. To help novice designers use prototypes more effectively, we must first determine how they currently use prototypes. In this paper, we describe how novice designers conceptualized prototypes and reported using them throughout a design project, and we compare reported prototyping use to prototyping best practices. We found that some of the reported prototyping practices by novice designers, such as using inexpensive prototypes early and using prototypes to define user requirements, occurred infrequently and lacked intentionality. Participants' initial descriptions of prototypes were less sophisticated than how they later described using them, and only upon prompted reflection did participants recognize more specific benefits of using prototypes.

Keywords: design education, novice designers, product design, prototypes, user centered design

Prototyping is a combination of methods that allows physical or visual form to be given to an idea (Kelley & Littman, 2006; Schrage, 2013) and plays an essential role in the product development process, enabling designers to specify design problems, meet user needs and engineering requirements, and verify design solutions (De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Moe, Jensen, & Wood, 2004; Viswanathan & Linsey, 2009; Yang & Epstein, 2005). Designers tend to think of prototypes as three-dimensional models, but nonphysical models, including 2D sketches and 3D CAD models, as well as existing products or artifacts, can also serve as prototypes (Hamon & Green, 2014; Ullman, Wood, & Craig, 1990; Wang, 2003).

Prototypes can help minimize design errors that may otherwise occur both early and late in the process. Often, prototypes can be created quickly and inexpensively and serve as effective models to help designers identify design issues and learn from failures (Kelley & Littman, 2006; Kordon & Luqi, 2002). Therefore, many advocates suggest that prototypes should be created early and used iteratively throughout the product design process (Clark &

Corresponding author:
Shanna R. Daly
srdaly@umich.edu

www.elsevier.com/locate/destud
0142-694X *Design Studies* **51** (2017) 25–65
http://dx.doi.org/10.1016/j.destud.2017.04.002

Fujimoto, 1991; Yock et al., 2015). Tom Kelley, chief executive officer of the global design firm IDEO, called prototyping 'the shorthand of innovation' and encourages rapid and frequent prototyping (Kelley, 2007). Schrage argued that prototypes should be regarded as disposable artifacts to discover opportunities and quickly eliminate less promising solutions (Schrage, 2013). This proposed 'quick and dirty' prototyping approach supports a greater number of iterations and enables designers to select the best solution to a design challenge without large amounts of 'sunk cost,' i.e. time and money, invested (Houde & Hill, 1997).

Expert designers leverage prior experiences to inform their design decision making processes and consider a broad spectrum of solutions before synthesizing information and selecting a concept for refinement (Cross, 2004; Ho, 2001; Lawson, 1994). Expert designers also use multiple and varied prototypes during all phases of product design (Crismond & Adams, 2012; Hilton, Linsey, & Goodman, 2015) to reduce complexity and achieve 'small wins' at the component level (Gerber, 2009). Working with prototypes at the component level and the ability to switch between component- and system-level thinking are crucial to successful design as practiced by design experts (Hilton et al., 2015; Viswanathan, Atilola, Goodman, & Linsey, 2014). A number of factors related to prototyping influence the design outcome, including the development of a structured approach for when and how to use prototypes, time spent on prototyping, and the complexity of the prototypes developed (Atman et al., 2007; Camburn, Dunlap, Kuhr, et al. 2013, 2015; Häggman, Tsai, Elsen, Honda, & Yang, 2015; Yang & Epstein, 2005). Design experts leverage their accumulated knowledge and experience and select the most appropriate approaches to prototyping to answer specific design questions (Houde & Hill, 1997) and rely heavily on prototypes to quickly test an idea or generate new ones. By doing so, they improve a concept and advance the design through the individual project phases (De Beer et al., 2009; Dow et al., 2010; Knapp, Zeratsky, & Kowitz, 2016).

The ability to demonstrate ideas through prototypes, rather than describing concepts verbally only, is critical early in a design project when developing a deep understanding of stakeholder needs (Skaggs, 2010). Stakeholders ultimately determine if a solution successfully addresses a design problem and therefore, stakeholders should be an integral part of the design process (Kelley, 2007; Schrage, 2013; Yock et al., 2015). However, eliciting and synthesizing sometimes conflicting stakeholder information can be difficult for designers (Mohedas, Daly, & Sienko, 2014c; Scott, 2008) and can lead to superficial design changes that do not address underlying deficiencies (Sugar, 2001). Prototypes are often the visual and tangible tools for communicating ideas, especially during the front-end phases of design, including problem definition and ideation (Goldschmidt, 2007; Koen et al., 2002, pp. 5–35; Mohedas, Daly, & Sienko, 2015; Mohedas, Sabet Sarvestani, Daly, & Sienko, 2015; Stempfle & Badke-Schaub, 2002; Yang & Epstein, 2005), when designers may share little or no common language with their targeted audiences (Kelley & Littman, 2006; Mohedas et al., 2014c). Here, prototypes provide a fundamentally different way of communicating around a 'shared space,' allowing stakeholders to interact with prototypes and to better articulate their needs and requirements to the designer.

Studies have shown that the behaviors of novice designers often differ from those of experts in key areas such as problem scoping, depth and breath of information sought, iteration and time spent during individual phases, and general design strategy (Atman et al., 2007; Miller & Summers, 2012; Mohedas, Daly, et al., 2015; Mohedas, Daly, & Sienko, 2016; Ozkan & Dogan, 2013; Popovic, 2004; Viswanathan, Atilola, Goodman, et al., 2014; Yang & Epstein, 2005). In contrast to design experts, novice designers often consider prototypes to be models that are created towards the end of a design process to test and evaluate a chosen design, rather than dynamic tools that can take various forms to help refine and develop several ideas in parallel (Hamon & Green, 2014; Lande & Leifer, 2009; Yang, 2009; Zemke, 2012).

Because of their limited domain knowledge and the lack of strategic frameworks for problem solving, novice designers are often unaware of the prototyping practices that might help them. The conscious reflection on what has been learned from previous prototypes can lead the expert designer to reframe the problem, add new requirements and/or make changes to a solution. But this implicit knowledge (knowing-in-action) that is necessary for action-oriented professions like design is difficult to describe and convey to novice designers (Schön, 1984). In addition to more extensive domain knowledge, studies on problem solving and human expertise have shown that experts have more conceptual and procedural knowledge than novices and that experts also organize this knowledge in ways that help them solve problems more effectively (Chase & Simon, 1973, 1988). The knowledge structures that, for example, expert chess players develop through deliberate practice, are what enable them to quickly recognize large chunks of domain-relevant information and determine suitable strategies and procedures for problem solving. These structures also provide frameworks to evaluate how effectively the problems are being solved and ultimately, to process new information about an unfamiliar domain (Nokes, Schunn, & Chi, 2010).

Developing an understanding for how novice designers currently use prototypes during a design process is crucial for establishing a baseline that lays the foundation for pedagogy and tools to support novices during their transitions to expert designers. Several studies have looked at expertise development and the strategic knowledge novices and expert designers use during design (e.g., Cross, 2004; Popovic, 2004), but there is a dearth of literature specifically focused on the use of prototypes throughout a design process. Other studies have reviewed how the use of prototypes during idea generation affects design fixation (e.g., Viswanathan, Atilola, Esposito, & Linsey, 2014), or investigated how the complexity and time spent on prototyping influences the design outcome (Atman et al., 2007; Häggman et al., 2015; Yang & Epstein, 2005), but these studies often focus on one aspect of a design process or were conducted in an experimental setting, instead of capturing novices' use of prototypes throughout the entire process (Atman et al., 2007; Hamon & Green, 2014; Kudrowitz & Wallace, 2013; Yang & Epstein, 2005).

Our research investigated how novice designers reported using prototypes throughout their semester-long engineering design processes. Since experimental settings without any long-term implications and personal investment such as grades might influence how participants behave, we studied participants' prototyping behaviors in context. Specifically, we investigated how novice designers reported using prototypes during a real design project, and compared their reported prototyping activities to prototyping best practice behaviors.

1 Research design

This study was designed to answer the following research questions:

- How do novice designers conceptualize prototypes?
- How do novice designers use prototypes in practice, including to engage with stakeholders?
- To what extent do novice designers use prototyping best practices?

We used a qualitative research approach for this study because we wanted to learn from participants' experiences and develop a deep understanding about their conceptions of and practices with prototypes. Qualitative research methods facilitate deep exploration of a particular topic (Boyatzis, 1998; Creswell, 2013; Patton, 2014) and have been used in numerous design practice studies (e.g., Adams, Daly, Mann, & Dall'Alba, 2011; Ahmed, Wallace, & Blessing, 2003; Ball & Ormerod, 2000; Bucciarelli, 1988; Cross, 2004; Daly, Adams, & Bodner, 2012; Daly, McGowan, & Papalambros, 2013; Daly & Yilmaz, 2015; Mohedas, Daly, et al., 2015; Mohedas, Daly, & Sienko, 2014a; Yilmaz & Seifert, 2011). To explore our research questions, we targeted novice engineering designers who had completed a project-based engineering design course during the prior semester at a large Midwestern university. The research project was approved by the university's Institutional Review Board.

1.1 Participants

A total of 16 students who had all completed a project-based, senior-level capstone design course at a large Midwestern university participated in this study. This number of participants is typical for qualitative research studies (Björklund, 2013; Cash, Elias, Dekoninck, & Culley, 2012; Crilly, 2015; Stempfle & Badke-Schaub, 2002) and allows for the use of interviewing to facilitate in-depth explorations of participants' experiences.

The majority of participants were completing undergraduate engineering degrees in disciplines such as mechanical engineering and biomedical engineering, however, two participants had higher education levels and had completed, or were currently enrolled, in a master's program. Half of the participants were female and half were male. Several participants also had other prior design or engineering practice experiences: half of the participants had referenced extracurricular academic design experience outside of their capstone design project, and four participants previously completed an internship or had limited work experience in design. All participants had completed a project-based capstone design course with similar requirements within the previous four months.

We considered the student participants to be novice designers because they had limited or no prior experience working on design projects that spanned a complete design process, e.g., from problem definition to evaluation, nor had they honed their design skills through extensive professional practice and interaction with stakeholders and clients. Some of the participants had more experience than others and therefore we expected a range of design and prototyping skills among them. For the majority of the participants, however, the capstone design course represented the first time they were asked to apply their previously learned design skills to a complex 'real world' design problem. The demographics of the participants including gender, design course, and prior design experience are shown in Table 1.

All three capstone design courses required participants to work in teams on a design project that included problem definition through the generation of user requirements and engineering specifications, concept generation and selection, and testing and evaluation. Even though different instructors taught the courses, all followed a common engineering design process (Dieter & Schmidt, 2012), had mandatory design reviews scheduled throughout the semester, required teams to produce physical models of their design, and included a final report at the end of the course. The individual projects were not situated in any particular field, and example projects included an automated heating and cooling vent, a medical device to stop internal bleeding, a food grinder, and sanitary pads for resource-limited settings.

Table 1 Participant demographics

Gender		*Capstone design course*			*Extracurricular academic design experience*		*Internship/work experience*		*Advanced education*	
Male	*Female*	*Mechanical engineering*	*Biomedical engineering*	*Multidisciplinary engineering*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
8	8	10	1	5	8	8	4	12	2	14

1.2 Interview protocol development

Data were collected through semi-structured interviews with the participants. Interview questions were designed to investigate how participants conceptualized and reported using prototypes during the individual design process stages. Questions helped to elicit information about the impact and benefits of prototypes during design, and the semi-structured interview format provided guidance to the participants as they reflected on the entirety of their design project while allowing them freedom to express their unique experiences and thoughts.

Interview questions were developed iteratively. The research team reviewed and refined the questions several times during study development. A pilot study with four participants, whose results are not included in this study, led to further refinements and the final versions of the interview questions. Questions were then categorized according to their relevance to prototype use and organized to follow a typical engineering design process. Table 2 shows the eight main question themes with examples of actual interview questions. The same interview protocol was used with all participants. Follow-up questions were also asked for clarification purposes or to encourage further elaboration on a particular comment.

1.3 Data collection

To recruit participants, the research team sent a mass email advertising the study to engineering design students who recently had completed a capstone engineering design course. The prerequisite for participation was the completion of such a course within the previous semester, and the interviews were performed approximately one month after completion. All participants were informed of the voluntary nature of their participation (i.e., their identity would not be revealed and participation in the study did not have any impact on their course grades) and given a $25 gift card for their contribution to the study. A single member of the research team conducted all 16 interviews. All participants gave their permission to have the interviews audio recorded for subsequent transcription, and names were replaced by numbers to ensure anonymity of the participants. The interviews lasted approximately 1 hour.

At the beginning of the interviews, participants were asked to define what a prototype is and does. Then the interviewer offered a broad definition of prototypes as 'three-dimensional physical models, CAD models or two-dimensional sketches or representations that communicate an idea or a design concept.' This broad definition, based on prominent design textbooks, was chosen and shared to ensure that participants would consider an inclusive definition of prototypes when discussing their projects, and it allowed for a subsequent evaluation of their prototyping behaviors compared to literature best practice.

Next, participants described their design project in chronological order and indicated during which phases of the project they used prototypes. The interviewer proceeded to ask the semi-structured interview questions and follow-up questions when necessary. As participants were describing their projects in more detail, some deviated from their original indications of when they had used prototypes and either changed or added prototyping activities to individual phases. In cases where a participant's use of prototypes did not match what they had previously indicated, the interviewer prompted the participant to elaborate on their statement for this particular phase.

While the first question captured participants' conceptions of prototypes (what a prototype is and does), the subsequent questions allowed participants to describe and reflect on their actual use of prototypes. The responses were coded to allow for the comparison of how participants conceived, and then described their actual use of prototypes. Example questions included:

- 'What prototypes did you use to understand the problem?'
- 'How did you use prototypes to develop user requirements?' and
- 'What role did prototypes play during stakeholder Interactions?'

1.4 Data analysis

First, all recorded interviews were transcribed and then examined by two editors for accuracy of the transcription. We then used a qualitative coding approach that included both inductive (Boyatzis, 1998; Creswell, 2013; Patton, 2014) and deductive (Crabtree & Miller, 1992) coding. For both coding approaches, we analyzed the transcribed interviews using QSR NVivo 10, a qualitative coding software.

Inductive coding is an iterative analysis of a data set, where patterns, themes and codes are allowed to emerge from the data instead of imposing previously identified codes on the data (Boyatzis, 1998; Creswell, 2013; Patton, 2014). In this study, we started by examining the transcripts and extracting excerpts related to the guiding research questions. Two researchers read through the interview transcripts and color-coded sections of recurring trends and patterns. These sections were then consolidated, and the researchers developed codes and descriptions that allowed these trends and patterns to be captured. The whole research team reviewed and coded the transcripts three times to ensure all critical information was captured. The codes were then grouped into the following categories:

- How novice designers defined what a prototype is and does
- When novice designers reported using prototypes
- How novices designers reported using prototypes
- How novices designers reported using prototypes to engage with stakeholders

Any particular segment of the interviews could be assigned more than one code, and the number of codes within a research question grouping varied from question to question. The code 'Communicate ideas,' for example, was based on quotes such as, 'If I imagine that I have to illustrate my idea with the stakeholders without the prototype, I cannot persuade them that this is a good idea'; 'Some people didn't really understand, so you have to bring the physical model'; and 'The more we showed [stakeholders] a prototype, the better our conversation was.' After the codes were finalized, and prior to the final round of coding all interviews, the researchers coded five randomly chosen interview transcripts with the coding list. An inter-rater reliability (degree of agreement between raters) was calculated to ensure a sufficient level of agreement between the two coders prior to coding all transcripts. The inter-rater reliability for the five initial interviews was 82%. The inter-rater reliability across all interview transcripts was 79% (75% is generally considered substantial agreement). Next, the raters discussed remaining discrepant coding results and reached full agreement prior to analyzing the findings.

Following the inductive coding analysis, a deductive coding approach was used, leveraging a framework we developed to represent prototyping best practices in design. We chose this approach to contextualize our findings about novice-reported usage of prototypes and to identify additional patterns and gaps in the data that were not captured by the inductive codes. The research team synthesized best practice behaviors from prominent design textbooks that are commonly referenced in engineering design courses to develop codes (Cross, 2007; Dieter & Schmidt, 2012; Ertas & Jones, 1996; Kelley & Littman, 2006; Otto & Wood, 2000; Schrage, 2013; Yock et al., 2015). While some research on prototyping practices in product design exists (Camburn, Dunlap, Viswanathan, et al., 2013; Christie et al., 2012, pp. 1154–1122; Viswanathan, 2012), textbooks that serve as standards for design process education provide more comprehensive coverage of prototypes than the current research literature. We used the collection of codes developed from our synthesis of prominent design textbooks to serve as a standard by which to evaluate novice behaviors and identify opportunities for improvement. And while not exhaustive, the codes developed represent a cross section of commonly cited

Table 2 Main question themes and example questions

Main themes	*Example questions*
General background	Could you please define what you think a prototype is? Could you please define what you think a prototype does?
Problem definition	How did you learn about the project? Describe the steps you took to understand the problem and challenges of this project. What prototypes did you use to understand the design problem?
Developing requirements and specification	What did you think was the most critical type of information to get from stakeholders? What methods did you use to develop the requirements and specifications? What methods did you use to prioritize the requirements?
Brainstorming and concept development	Describe the methods you used for brainstorming ideas. What methods did you use to develop concepts? How did you select the ideas you thought worth pursuing?
Evaluation and concept evaluation	How many concepts did you evaluate? What methods did you use to evaluate your concepts? Were your stakeholders involved in evaluating your concepts?
Building physical models	What were some of the compromises that you had to make while building your prototypes? Describe your strategy for building these prototypes. Did you have a drawing, a CAD model, etc. prior to starting your build? What did you learn from your prototypes?
Testing and evaluating	What evaluation methods did you use for your concept? How did you test your final model?
Prototyping in general	How did physical prototypes impact your overall design outcome? What role did prototypes play with stakeholder Interactions? At what project stage were prototypes most helpful?

prototyping best practices. We then used a deductive coding approach with this prototyping best practice framework to evaluate participants' descriptions of specific prototyping practices (Table 3).

Using the list of prototyping best practice codes, each participant was rated on a 3-point scale (0-1-2) based on the extent to which his or her behavior met specific prototyping best practice behaviors, considering the intentionality, level of refinement, mode of construction, iteration, and timing of reported prototyping activities. The following criteria were used for the ratings, and descriptions of how the ratings were interpreted for each best practice are included in Appendix A:

(0) indicated little or no evidence of the behavior
(1) indicated some evidence of an intermediate behavior
(2) indicated evidence that participant's behavior aligned with best practice

After the codes and definitions were finalized by the research team, and prior to coding all interviews, two researchers coded five interview transcripts with the coding list. An inter-rater reliability was calculated (83%) and the coders reached consensus on the discrepant coding results prior to coding all interviews.

2 Findings

In the following sections, we describe key patterns that emerged from our analyses of novice designers' conceptions of the role of prototypes and the descriptions of how they reported using prototypes in their design processes. Example excerpts are included throughout, however, codes were developed based on the full transcripts.

2.1 How did novice designers conceptualize prototypes?

Novice designers' descriptions of what prototypes are ranged from physical, tangible models to unfinished and incomplete models, to models that could be both physical as well as virtual. Novices' descriptions of what prototypes do included 'Demonstrates form and function', 'Tests design or proves a concept', 'Identifies next steps' and 'Communicates', and demonstrated notable variations in novice designers' conceptions of what prototypes are and do. The codes, their corresponding definitions, frequencies, and example data excerpts for these two questions are included in Tables 4 and 5, and a discussion of the most and least frequently mentioned codes follows.

Table 3 Codes describing prototyping best practices

Best practice	*Definition*
Design the minimal model needed	Only what is needed to answer the question is prototyped, leaving off unnecessary features
Develop prototypes of multiple concepts in parallel	Multiple concepts are prototyped at once to select the most promising approach
Identify, prioritize, and isolate functional blocks of prototypes	Features (functional, aesthetic, etc.) that need to be prototyped are determined
Reassemble blocks into complete concept models	Re-integrate what has been learned from the functional block into the whole concept model
Use appropriate types of prototypes to address specific design questions	Select the best suited prototype format to address a specific question
Use inexpensive prototypes early and efficiently	Simple and cheap concept models are built to learn additional information (trial and error prototyping)
Use prototyping iteratively and develop increasingly refined prototypes	Prototypes get more and more refined and incorporate additional knowledge
Use prototypes to answer specific design questions	A specific question is identified and prototypes are created to find the answer
Use prototypes to communicate design concepts	Prototypes are used to communicate ideas to team members and stakeholders
Use prototypes to define design problems	Early use of prototypes leads to defining of design requirements and specifications
Use prototypes to engage with stakeholders	Prototypes are used to engage with stakeholders to gather input and feedback
Use prototypes to refine design problem definitions	Later use of prototypes leads to refining of design requirements and specifications
Use prototypes to test concepts	Prototypes are used to test a concept or idea
Use readily accessible and applicable existing objects or combinations of objects as prototypes	Existing products or parts are utilized and/or incorporated into a prototype
Vary the scale of prototypes	The scale of a prototype is adjusted when appropriate to make construction easier

Table 4 Codes describing how novice designers defined what a prototype is

Code	*Definition*	*# of participants (of 16)*	*Example quote*
Tangible model	A physical model that can be felt or touched, not virtual/CAD.	6	I would think of a prototype in a physical form rather than a computer model, so something that you could hold and see.
Work in progress	A model that does not have to be finished and can still be modified.	6	A prototype is a mockup of a product you're working on…It's either not designed perfectly or not actually functional… It's creating a physical representation of an idea that's not finished, but it answers some questions.
Representation that doesn't maintain all properties	A representation where the physical properties such as size and material can vary from the finished product.	5	[A prototype] doesn't necessarily have to be made of the correct materials or be the correct size. It could be something that's scaled down…
Part of a complete design	An essential component or a part of the final design that doesn't have to represent the whole assembly.	3	[A prototype] could be…just a sub-assembly that's put together to show how a particular subset of a machine will work.
Three-dimensional object	A three-dimensional object that can be physical and/or virtual/CAD.	2	[A prototype] doesn't actually have to be a physical thing that you can use, but it could be CAD.

The two most frequent aspects novice designers emphasized in their definitions of prototypes were 'Tangible model' and 'Work in progress.' Six participants stated that prototypes did not need to be complete but could be a 'work in progress.' For example: 'a prototype is a first-run mock-up of whatever design you're working on. It might not be exactly what the end product is going to be, but more of a proof of concept and showing that what you're designing will work after several reiterations' (Participant 5); 'your first variation of the project… It might not be your final design' (Participant 10); and 'a representation of an idea that's not finished, but it answers some questions' (Participant 12).

Six participants defined prototypes as physical, tangible models that can be touched. For example: 'That's some sort of a physical representation of something you're trying to make' (Participant 11); 'I view a prototype as something physically built' (Participant 13); and 'I think of it in a physical form rather than maybe a computer model, so something that you could hold and see' (Participant 15). While six participants described the physical nature of prototypes, only two described prototypes as including virtual (CAD) objects as well. For example: 'It doesn't actually have to be a physical thing that you can use, but it could be CAD or something' (Participant 14).

Table 5 Codes describing how novice designers defined what a prototype does

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Demonstrates form and function	Something that demonstrates what a device looks like and how it functions.	8	A prototype is anything that's built to either show the form or function of a final design.
Tests design or proves a concept	Something that allows the testing of certain aspects of the design like shape and strength and demonstrates feasibility.	8	Mainly you would build the prototype, so you could test certain aspects of the design, either the shapes or the strengths or maybe cost assessment.
Identifies next steps	Something that allows for a different perspective or assessment, helps to identify what else needs to be done, and/or moves the project through the phases.	3	A prototype is partially a result of the design process that you're going through. It's going to help you identify what other things you need to pursue while you're in the design process.
Communicates	Something that helps to transfer knowledge of an idea or concept to others and/or gather input and feedback from others.	3	It's a really great tool that you can bring in to stakeholders, saying, 'What do you think of our current design, and what can be added or taken away?'

Five participants claimed that prototypes did not need to maintain the fidelity of a final model and could compromise properties such as scale and materials. For example: 'It could be a scale model that just shows how things are going to come together' (Participant 2); 'It doesn't necessarily have to be made of the correct materials or be the correct size' (Participant 8); and 'A prototype would be a model, sometimes a smaller version of some product that you want to make. It could be a smaller version of a big thing' (Participant 15).

Three participants discussed that a prototype could represent part of a complete design, i.e., a single component that does not necessarily represent the whole product. For example: 'Just a sub-assembly that's put together to show how a particular subset of a machine will work' (Participant 2); 'It's just to answer one piece of the question… One piece of like, "What is it look like? Does this piece work? Can people hold this? Do that?"' (Participant 12); and 'it could be part, certain parts of the final product, so it doesn't necessarily have to totally resemble the final product' (Participant 15).

With regard to what prototypes do, half of the participants said that prototypes are used to demonstrate form and/or function, for example: 'I'd say a prototype is anything that's built to either show the form or function of a final design' (Participant 2); 'It demonstrates whatever core functions of your design need to… your final design needs to be able to perform' (Participant 8); and 'It's the first fully done design, something that executes form and function' (Participant 14).

The other most frequently mentioned role for prototypes, discussed by eight participants, was that prototypes are used to test or prove a design or concept. For example, 'More of a proof of concept and showing that what you're designing will work after several reiterations' (Participant 5); 'It might be even something just to test it, but you're making it to see whether your design actually works' (Participant 10); and 'You are doing this to validate, to make sure it works before you create a final design' (Participant 16).

Three participants thought that prototypes could be used to identify the next steps in the design process. Participant 13 explained, 'It's a tool to go from the planning stage to the making stage … once you actually build something physical, you see all these things you never thought of before in the planning stage. It's usually like, "This doesn't fit the same way" or "We could do this better" because just visually holding the object in your hand gives you kind of a different perspective on the design.'

Only three of the participants described prototypes as communication tools to share ideas and gather feedback from others. For example, 'I think it's a really great tool that you can bring in to stakeholders, saying, "What do you think of our current design, and what can be added or taken away?"' (Participant 7) and 'Another thing is to show the people who you want to convince, like the board of the company or anything, the teacher or professor or anyone… Anyone that "Okay, this is our concept and it works"' (Participant 3).

2.2 When did novice designers report using prototypes in practice?

To answer this question, we analyzed participants' descriptions of their use of prototypes according to common stages in the design process. Across all participants, novice designers reported using prototypes during all phases of their design project, but not everyone used them in all phases. All participants reporting the use of prototypes for idea generation and testing, and the fewest participants reporting the use of prototypes for the development of user requirements and engineering specifications. The codes, their corresponding definitions, frequencies, and example data excerpts for this question are included in Table 6, and a discussion of the most and least frequently mentioned codes follows.

The two most frequently cited phases in the design process where participants reported using prototypes were 'Concept or Idea Generation' and 'Testing and Evaluating.' All 16 participants reported that they used prototypes in these two phases, but participants reported using different types of prototypes. During 'Concept or Idea Generation,' participants tended to use low-fidelity prototypes such as sketches and mockups. For example, 'We made sketches for possible solutions to each sub-function' (Participant 4); 'Some of the ideas that were really hard to explain were actually easy if you cut a piece of cardboard' (Participant 6); and 'We started drawing a lot of things out. A lot of ideas. Each of our group members drew about 10–15 designs on paper just to look at what ideas we can use and how this would meet our engineering specs' (Participant 16).

During 'Testing and Evaluating,' however, participants used more refined higher-fidelity prototypes, including 3D printed models. For example, 'Once we had actually built the prototype, then we made this pulp out of paper and water, put it onto the screen and frame that we had built, put it into the press, pressed it, extracted the water, measured how much water we were able to extract, measured the time that it took for it to dry' (Participant 4); and 'It's one thing to build a model that is nice to look at, but if you can actually get to functionality and testing some certain functionalities with your prototype, then that's going to be really useful in the long run' (Participant 15).

The least frequently cited phases in the design process for which participants reported using prototypes were 'User Requirements' and 'Engineering Specifications.' Only 10 participants reported the use of prototypes during these phases, and the reported activities in these two phases often went hand in hand. For example, 'User requirements… Ability to load easily was a user requirement. An engineering spec based on that was an opening width of the container of some form. In doing that, we looked at existing products, existing spice jars basically' (Participant 11); 'One of the user requirements had to do with ease of movement of the cube. We went around [and] performed some tests on various objects' (Participant 8); and 'For user requirements and engineering aspects, we did some sketches there to try to figure out overall what we are doing' (Participant 16).

Additional findings included two participants reporting that prototypes enhanced collaboration within their team during the concept generation and building phases. For example, 'It helped bring us closer together as a team. Because there's a physical object, you have to spend physical hours and time with each other in the same space. I think it helped build relationships in that way. We couldn't divide up work necessarily and go off on our own. We actually had to work together' (Participant 13) and 'I think it helped us to work together to talk out our ideas and to convince each other one way or the other if it would work or not or to play devil's advocate and be like, "Well, I don't think that's going to work." I think it helped our team work together' (Participant 9).

Other participants described wanting to use prototypes more often or during different phases in their design projects: 'I think just the very structured way the course is taught probably leads a lot of people to think, "Maybe we shouldn't be doing this portion; maybe we should be focusing on just building

Table 6 Codes describing when novice designers reported using prototypes

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Concept or idea generation	Used prototypes to generate multiple ideas and concepts that solve the design problem.	16	The ideas that were developed, instantly we sketched them up. I also said that we had some primitive mock-ups here because some of the ideas that were really hard to explain were actually easy if you cut a piece of cardboard …
Testing and evaluation	Used physical models to ensure that the design solves the initially stated problem and that it also satisfies requirements and specifications defined in earlier stages.	16	We identified how long it usually took doctors to use the [device]. We compared that time to the amount of time it took for students…we would just show people how to use the device through an instructional video…they would follow the steps…and do the same procedure, and we'd time how long it would take for them to do that. Consistently, it's been shorter than the actual, original method.
Problem definition	Used prototypes to help understand and describe the problem/need and demonstrate the importance of a solution.	15	Seeing how things were currently done was useful and we were actually able to see that. It was just the screens just being set directly out in the sun. We knew since that's how it was currently working, that we had to take it steps further than that.
Concept selection	Used prototypes to select or narrow down the concepts, eliminating ideas that do not meet requirements or specifications and/or choosing ideas that best solve the design challenge.	15	We wanted to get some more concrete method for selecting stuff…We did some preliminary testing in the concept selection, and…worked to actually build prototype screens… We decided to do it because we felt uncertain about how we were evaluating our concepts.
Engineering analysis	Used prototypes for theoretical evaluation prior to physical build.	14	He just went back to build the whole thing in SOLIDWORKS…Then they have FEA analysis. It's really easy to calculate all the force, strength, and to see if it works or not. Also, I did all the mechanics calculations by hand, really easy sketches…

(*continued on next page*)

Table 6 (*continued*)

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Building phase	Built refined, physical models in this phase to represent and capture the combined outcome of the previous phases.	14	[The specific goals for building the physical model were] to see if it was feasible, to see if it would work. Because it works on paper and in CAD, but it doesn't necessarily mean that will work in the physical world.
User requirements	Used prototypes to learn about user experiences and develop needs and characteristics that the design must meet to be considered successful by the end user.	10	I didn't get it. Why was it so hard to load the truck?...We bought a big board. It was not that heavy, but it wasn't possible for me to load it myself on the truck…These are the ways that we had to figure out 'Okay, what's the problem? What do they need?'
Engineering specifications	Used prototypes to create engineering specifications that are quantitative measurements that the design must satisfy. Specifications must contain target values and engineering units.	10	[People] would find something around them and be like, 'This is portable.' We would take that, and we would weigh after they told us about it. We would measure it and see the size.

things." I think that was one of the major reasons why we didn't sketch, because I feel like if we did sketch at that point, a lot of us would feel like we'd be wasting time, like, "Why are we sketching? We should be building things"' (Participant 7) and 'They wanted us to do in-depth engineering analysis… differential equations and really proving that what we were going to do worked. Whereas we were building something out of wood and PVC, so we figured, "Let's just build it and then we'll go through it"' (Participant 2).

2.3 How did novice designers report using prototypes in practice?

Fifteen ways in which novice designers reported using prototypes throughout their design projects emerged from our analysis. These ranged from the most participants engaging in 'Test and evaluate' and 'Communicate' to the fewest participants engaging in 'Iterate intentionally' and 'Evaluate user interface.' The findings from these codes are summarized in Table 7, and we discuss the most and least frequently mentioned codes below.

The most frequent way participants cited the use of prototypes occurred later in the process when they reported using them for testing and evaluating a chosen design concept. Participants often stated that only with the help of a physical model could they evaluate the design effectively and that evaluation

Table 7 Codes describing how novice designers reported using prototypes

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Test and evaluate	Prototypes are used to test and evaluate the process as well as the outcome/ product. Prototypes are used to prove that the selected concept works. Occurs after building phase.	16	With the final prototype, we were able to really validate our design and figure out what could be improved in future durations of the design. Having a physical model at the end of the day is really important because otherwise you can't validate your design effectively.
Communicate	Prototypes are used as a tool to convey ideas, avoid misunderstandings and improve individual comprehension among the students and their team members.	16	The prototypes…were all used as communication tools… that impacted the team and our ability to better understand what somebody was talking about or referring to.
Generate ideas	Prototypes helped when the team brainstormed ideas, often using sketches or mockups as tools to organize thoughts and ideas.	15	For each sub-function, we each took some time by ourselves to draw up at least five ideas, and then we came back together and shared all of those. As we were sharing them, we'd oftentimes spark an idea from someone else's design.
Iterate unintentionally	Physical models reveal unexpected challenges. Unanticipated iterations are sometimes necessary as a result. (Examples: Tolerances are not included in the CAD model, the physical model turns out not exactly like the CAD model, etc.)	15	You think you know your problem, and then you make the prototype. And you'll be like, 'Oh, I actually don't think that was the problem. I think it's this instead.'
Understand the problem	Prototypes including existing products are used to understand and define the problem that will focus and guide the project.	14	I have never used one of these products before or seen one, so it's nice to get the feel of what it was supposed to do and how it was supposed to operate when we were designing what our new one was going to be like.

(*continued on next page*)

Table 7 (*continued*)

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Demonstrate form and function	Used physical models to show the shape and size of the selected concept as well as how the concept works.	13	Without our primitive mock-up, we wouldn't have really been sure about things working and really being able to visualize it. Then it's that ability to see each individual piece.
Select a concept	Prototypes helped the team pick a final concept to pursue with a formalized methodology or design matrix such as a Pugh chart, concept tree, etc.	13	With the sketches and with the dimensions, we made a Pugh chart and we down-selected from there.
Test sub-components	Prototypes, physical or CAD models of individual pieces or parts rather than the whole assembly are evaluated.	13	We tested the circuitry components separate from the physical movement…We tested the code and the circuitry separate from the physical…We tested the physical as well without SMA actually actuating.
Analyze	Prototypes are used in theoretical evaluation like stress analysis and performance of selected concepts. Not rigorous testing and validation. Occurs prior to building phase.	13	We built the CAD model and then… we were analyzing all the forces. From that, we were able to fully define the model and figure out exact dimensions that we needed.
Visualize	Prototypes are used to help envision what an idea would look like.	12	As far as sharing ideas, it was really, really helpful to have the sketches and to be able to…get inside each others' head to see what people meant by what they were saying.
Evaluate early	Quick and rough prototypes are used for early/front end evaluation.	11	But then when we got to the concept selection phase and we were doing some of this testing stuff which I'm considering this as prototyping, we revisited some of these ideas that we had passed off before because we wanted to evaluate them to some amount. That's what led us to the change of direction, change of path in our project.

(*continued on next page*)

Table 7 (*continued*)

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Delegate	Prototypes are used to assign responsibilities and tasks to members of the project team.	11	We all had our different skills that we were good at, and we were able to find that and distribute what needed to be done pretty evenly and effectively.
Collaborate	Prototypes are used by students to engage with others.	10	Because there's a physical object, you have to spend physical hours and time with each other in the same space.…We couldn't divide up work necessarily and go off on our own. We actually had worked together.
Iterate intentionally	Physical prototypes are intentionally built to work out details and expected challenges. Students know that iterations are necessary, following earlier prototyping. Example: It can be easier to figure out some details by trial and error in the physical model than by CAD and math calculations.	9	We thought about the sliding issue a little bit, but we wanted to see what it would actually do when we started using it. You can't really know how it would actually work until it is produced and sitting on top of the bucket and rolling.
Evaluate user interface	Prototypes are used to evaluate interaction with the design such as ergonomics or human factors.	8	[Our initial prototype] just felt wrong because you had to overlap your fingers…When we made it bigger for the things inside, it also helped the feel of it as well.

through other forms of prototypes was not feasible. For example, 'Having a physical model at the end of the day is really important because otherwise you can't validate your design effectively' (Participant 4); 'You can't really validate a drawing… You can validate CAD to some extent, but physical is definitely the best' (Participant 16); and 'It's one thing to build a model that is nice to look at, but if you can actually get to functionality and testing some certain functionalities with your prototype, then that's going to be really useful in the long run' (Participant 15).

All 16 participants also reported using prototypes to communicate, including to convey ideas, avoid misunderstandings, and improve comprehension of a concept among stakeholders, instructors, and team members. For example:

'It would just be our main method of translating information from my mind to somebody else's mind. — Because as far as sharing ideas, it was really, really helpful… to be able to more get inside each others' head to see what people meant by what they were saying' (Participant 11); 'If someone explains something physical to me, I'm not going to get it until I can see it on paper. I can try, but I guess I'm not confident that how I'm understanding it is correct until I can see it visually' (Participant 13); and 'The prototypes, or prototyping in the form of sketches, in the form of physical materials, were all used as communication tools. I think that impacted the team and our ability to better understand what somebody was talking about or referring to' (Participant 11).

The least frequently mentioned use of prototypes was to 'Evaluate user interface.' Only eight of the 16 respondents said that they used prototypes for this task with members of their team or with outside groups like stakeholders. The types of user interface evaluations participants performed with their prototypes fell into two distinct groups: Ease of Use or Comfort Assessment. For example: 'We used [our prototype] on some of our classmates to time how long it would take to set up and to inflate' (Participant 9) and 'We set up our [prototype] in the atrium… and we basically just got random people to sit on our [prototype]… we had a huge checklist for how to rate our [prototype] based on comfort' (Participant 10).

The second least frequently mentioned use of prototypes was for 'Iterate intentionally' wherein physical models were intentionally built to work out challenges. Nine participants built prototypes expecting that they would have to make changes based on what they learned from the models. For example: 'We built a physical model. That was a way to see whether our ideas were even working. You can have something on paper and not realize that it's going to have interference' (Participant 10) and 'Let's see if it works. If it doesn't, we can take a look and try to troubleshoot it. If it does, maybe we can use it for the final one anyway' (Participant 11).

The low volume of quotes in which participants mentioned 'Iterate intentionally' contrasted with 'Iterate unintentionally,' which was mentioned by 15 participants. Here, physical models revealed unexpected challenges that required unanticipated changes. For example: 'You think you know your problem, and then you make the prototype. And you'll be like, "Oh, I actually don't think that was the problem. I think it's this instead"' (Participant 12); and 'Then after making these mockups and designing some of these preliminary CAD models, we ran into some things. We're like 'okay, we clearly haven't thought about this enough. That's going to be an issue to worry about.' I think that's really one of the best advantages of doing those preliminary prototypes' (Participant 15).

Table 8 Codes for how novice designers reported using prototypes to engage with stakeholders

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Communicate ideas	Used prototypes to share concepts and thoughts with at least one stakeholder at least once in the process. This includes sketches, pictures, videos, and CAD models.	16	The more we showed them a prototype, the better our conversation was…when you're looking at something, you can say, 'No, this arrow is on the wrong spot. That's not how that works.' Or if it's a physical one, to say, 'I would never hold this way, or this is too big,' things like that.
Demonstrate form and function	Used physical models to show stakeholders the shape and size of the selected concept as well as how the concept works.	13	Some people didn't really understand, so you have to bring the physical model to see, to show what it looks like.
Gather feedback	Used prototypes to obtain assessments from stakeholders on the whole design or individual functions that can influence design decisions.	13	When we showed our physical models to doctors, they gave us feedback, and we were able to use the feedback to make changes.
Define problem	Used prototypes with stakeholders for understanding the problem that will focus and guide the entirety of the project.	10	We didn't have prototypes that we made, but they certainly used objects to demonstrate things.
Evaluate user interface	Gave prototypes to stakeholders to evaluate interaction with the design such as ergonomics or human factors.	9	(We) had people come and use our machine and see, without any instruction from us, how they would use it and how comfortable it was to use.
Mark progression	Used prototypes as a checkpoint with stakeholders to show design continuation and changes.	6	We never actually got to meet him face-to-face, but the whole way down the project we were showing him. We were taking pictures, communicating with him. The whole time during this, as we progress with the project, we were showing him how we were doing it and everything.
Observe	Used prototypes to witness how users interacted with models.	6	We invited some people in to use it. We found that people like to jump on the foot pedal rather than just gently press it.

(*continued on next page*)

Table 8 (*continued*)

Code	*Definition*	*# of participants (of 16)*	*Example quotes*
Select concept	Used prototypes to allow stakeholders to help select the final concept or provide input that led to final concept selection.	6	In the end, we base on our survey result to choose the final one.
Test and evaluate	Used prototypes to show stakeholders that their idea/concept works and satisfies the requirements.	6	We'd do it to random people. We'd be like, 'You feel it? It's getting cold?' They're like, 'Yeah.' I'm like, 'Great, good. Feel it? This feels good?' 'Yeah, I could use this,' kind of thing.
Persuade	Used prototypes to motivate stakeholders to endorse a design change.	2	If I imagine that I have to illustrate my idea with the stakeholders without the prototype, I cannot persuade them that this is a good idea.

In addition to physical prototypes, all teams created virtual CAD models prior to building their final physical model, an activity that participants found both helpful and challenging. For example, 'The CAD models really helped us to figure out what kind of problems we might run into. That helped us have more realistic design that was then much easier to turn into a physical model' (Participant 15). In contrast, 'The concept in SOLIDWORKS was all right. It looked nice and everything… but obviously, in SOLIDWORKS, your [model] is not going to tip over' (Participant 10).

2.4 *How did novice designers report using prototypes in practice to engage with stakeholders?*

Since it is critical to engage stakeholders throughout the design process, we included a specific focus on how novices reported using prototypes to engage with stakeholders. Participants' reported use of prototypes with stakeholders ranged from high frequency behaviors like 'Communicate ideas' and 'Demonstrate form and function' to low frequency behaviors like 'Select concept' and 'Persuade stakeholders.' A summary of the coding schemes and frequencies is included in Table 8, and we discuss the most and least frequently mentioned codes below.

Participants most frequently reported using prototypes to engage with stakeholders when communicating ideas. All 16 participants mentioned at least once that they used prototypes such as sketches, pictures, videos, and CAD models to share concepts and thoughts with some of their stakeholders. When sharing ideas, prototypes provided a unique form of communication that allowed people to understand ideas in different ways. The interaction that occurred when supporting communication with prototypes promoted a more comprehensive understanding of an idea beyond a verbal description alone. For example: 'I think without the prototype, it would be hard for stakeholders to imagine what exactly you were trying to say/talk about' (Participant 7); 'The more we showed them a prototype, the better our conversation was… The more prototypes we brought with, the better the conversation was' (Participant 12); and 'With our engineering professor, the CAD [model] was most helpful with him because he understood. The more physical things like the sketches on paper were more helpful with the doctors' (Participant 14). It is noteworthy to mention that even though all participants used prototypes to engage with stakeholders at some point, six participants also described missed opportunities, instances where they could have used prototypes with stakeholders, but didn't.

The second and third most frequent prototype uses with stakeholders were 'Demonstrate form and function' and 'Gather feedback.' Thirteen participants said that they used prototypes to obtain assessments from stakeholders on the whole design or individual elements that then influenced their design decisions. These behaviors are related to communicating ideas, but in addition to communicating, here designers actively collected and incorporated feedback to improve their design. For example: 'Prototypes were big in allowing us to communicate our ideas with the professors and show where we were going. Then we could have some back and forth and talk about our ideas and make tweaks…' (Participant 2) and 'We sent them sketches of each [concept] and a little description of what our goal or intention was for each of the concepts and had them give us feedback on each one. Then once we did select it, we said, "This is what we're selecting, is this okay with you?" They thought it was a good idea' (Participant 9).

Participants least frequently reported using prototypes to persuade stakeholders of the validity of a concept early in the process or endorse a design change later in the process. Both participants who referenced this intentional prototyping activity had more experience through work on undergraduate project teams or in industry. Participant 1 called upon his prior design background to describe a theoretical situation: 'If I imagine that I have to illustrate my idea with the stakeholders without the prototype, I cannot persuade them that this is a good idea. But if I have a 3-dimensional prototype to show them how [it] can be worked…I think that's helpful.'

Despite many participants citing the usefulness of prototypes during their interaction with stakeholders, not all participants mentioned that they used prototypes to gather feedback from stakeholders. This may be due to a number of reasons, including that they did not have access to a particular stakeholder group like their intended end users or they did not think to use prototypes in a certain way to engage with stakeholders. In retrospect, when reflecting on their experiences with stakeholders, some participants stated that they would have liked more input and regretted this missed opportunity: 'Maybe they would help us down-select in our Pugh chart because a lot of the requirements that we made were based on what they said. Then they can tell us"No, you totally misinterpreted what I was thinking there." That would be cool. We didn't get any of that feedback' (Participant 6).

2.5 To what extent did novice designers engage in prototyping best practice behaviors?

The outcomes of the inductive coding analysis shed light on how novice designers conceptualized prototypes as well as when and how they reported using prototypes in practice, including to engage with stakeholders. And even though their conceptions of prototypes were limited in quality and frequency, participants later described using a variety of prototypes during many phases of their projects. As a result of these findings, the authors continued to have questions about these reported behaviors and how they compared to prototyping best practice. Were novice designers indeed leveraging best practice behaviors in prototyping?

We found that participants most frequently followed prototyping best practices for 'Use prototypes to test concepts' and 'Use prototypes to answer specific questions.' Participants less frequently followed prototyping best practice for 'Vary the scale of prototypes' and 'Reassemble functional blocks.' Detailed results are shown in Figure 1, and we discuss the most and least frequent reported behaviors below.

We evaluated not only the occurrence of each prototyping best practice behavior but also the quality and found that participants engaged in a number of prototyping best practice behaviors. The most frequently occurring prototyping best practice behavior was 'Use prototypes to test concepts.' In contrast with their earlier definition of what prototypes do (only eight participants mentioned that prototypes are used for testing), all participants engaged in this behavior, and 13 out of 16 participants performed in accordance with best practice. For example: 'Having a physical model at the end of the day is really important because otherwise you can't test your design effectively. With the final prototype, we were able to really test our design and figure out what could be improved in future iterations of the design' (Participant 4) and 'I think we went through maybe three or four, maybe even five, design iterations. We're able to test all of them, all of these prototypes' (Participant 15).

However, some participants performed only at an intermediate level, and testing revealed unexpected challenges for those teams. For example: 'As we

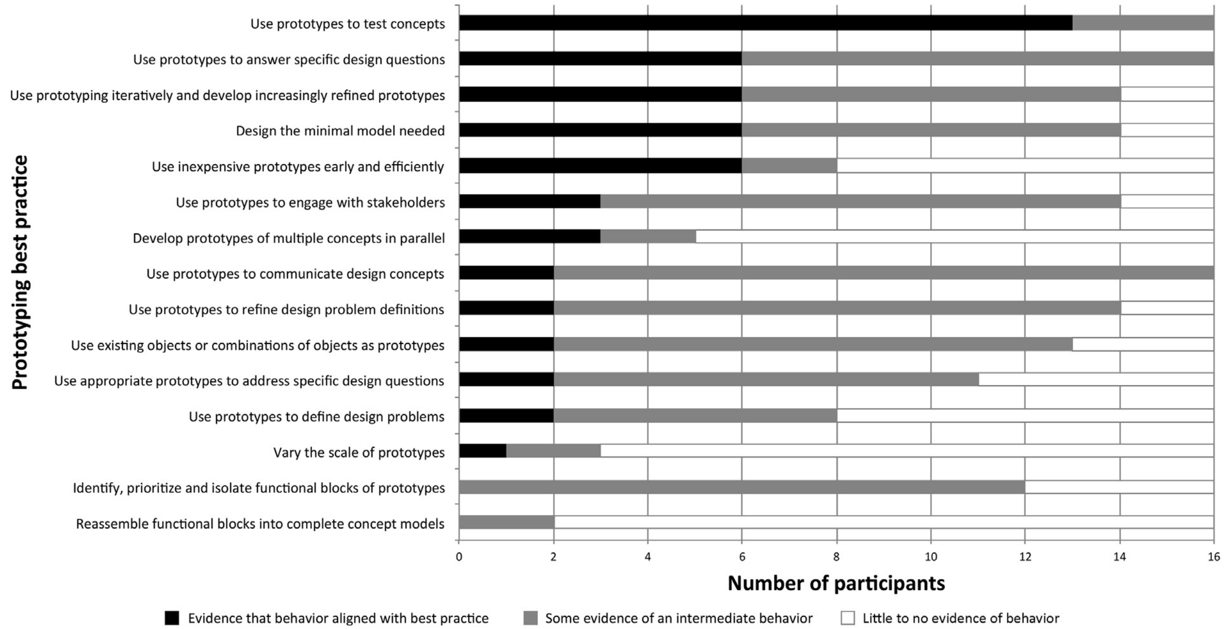

Figure 1 To what extent did novice designers engage in prototyping best practice?

were trying to test [the prototype], we kept hitting these hurdles, and realized this is going to be a lot more in-depth to try to test this than we anticipated' (Participant 12) and 'We kind of just had one physical model, but… we weren't trying to find every place of failure' (Participant 10).

The next highest frequency best practice behavior across participants was 'Use prototypes to answer specific design questions.' None of the participants had mentioned this use early in the interview when asked about their conception of prototypes, and only three participants said that prototypes could be used to identify next steps, a somewhat related behavior. However, during the discussion of their design project, all participants reported engaging in this behavior. For example: 'For engineering analysis, we wanted to analyze the tension and the pulling force. Because we're doing a rough prototype, we just used a water bottle. We just put the [object] in the water bottle and just pulled it out. We measured how much force, which direction you have to pull, and how big an opening' (Participant 1).

In contrast, Participant 3, who performed at the intermediate level for this behavior, explained how use of a CAD model was less intentional and more incomplete and exploratory in nature: 'We didn't have a dynamic simulation, so you don't actually know how it moves.'

When defining prototypes early in the interviews, only two participants mentioned that prototypes could be used to communicate, and communication was not a direct requirement of the course. However, when describing their projects, all participants engaged in the prototyping best practice behavior 'Use prototypes to communicate design concepts.' We found that only two participants performed in accordance with this best practice behavior; the remaining 14 participants all engaged at the intermediate level. The participants we recorded in accordance with this behavior reported deliberate prototyping to aid in the communication of their design concepts, and Participant 6 elaborated: 'I also said that we had some primitive mockups here because some of the ideas that were really hard to explain were actually easy if you cut a piece of cardboard …it was two dimensional, but it still moved, so we had a couple of mockups of that showing how it would work.'

Only three participants performed in accordance with the behavior 'Engage with stakeholders,' and only one participant had mentioned stakeholders when giving their early definitions of prototypes. When describing their project, a participant who had designed a device for the visually impaired asked stakeholders to evaluate a thumb-actuated feature. Only by deliberately asking their stakeholders to interact with the prototype did the team learn that people with visual impairments typically identify features with their index finger, not their thumb, which then led to changes in the design concept. 'Finding information with the pointer finger, that's so not intuitive for somebody who is not blind or visually impaired. If you grab something like this, usually it's your thumb' (Participant 11).

Eleven participants frequently engaged with stakeholders with less intention, later in the project, or did not ask questions to elicit feedback. For example: 'We'd send them pictures, we'd send them our CAD. We just tried to keep them up to date because it was their money' (Participant 14) and 'Basically from observation, it's simple. You can see, "Okay, what's the biggest problem?" Then we saw some people with a big chunk of stuff, that's not necessarily heavy. We found that, he finally had to get somebody from the store to help him load it up' (Participant 3). The same team later considered themselves as end users for evaluating their proposed solution, instead of engaging real owners: 'We tested how far you could reach with your arm, to pull things out. It was 42% of the whole area of the truck's back. With our product it was 33… no it was 83%. That met the requirement, that you could reach most of the truck's back' (Participant 3).

The prototyping best practice behavior 'Use inexpensive prototypes early and efficiently' was used according to best practice by half of the participants. The other half of participants showed little to no evidence of this behavior. This is the only behavior for which we observed this type of distribution. To illustrate a successful engagement in this behavior, as Participant 14 explained, they used primitive and readily available objects to determine the best way to position features on a small, handheld medical device: 'At that point, we didn't have our wood model. I think we used pens and things. We were like, 'Well, if we were like this, if we were like that, how would that be easiest?''

In contrast, Participant 8 had the same opportunity, but instead chose to use sketches only instead of physical models to evaluate ideas and select the most promising concept for a rotating mechanism: 'We were starting to look at the pros and cons of different sketches and pulling elements of certain ones like, "We like how the main shaft goes through here. We like that it's mounted at an angle in this one." It felt like no new ideas are coming. "Let's start looking at the ones we have."'

The lowest reported usage of a prototyping best practice behavior was 'Reassemble blocks into complete concept models' with only two participants reporting the behavior. While 12 participants engaged in the related 'Identify and prioritize functional blocks' behavior, only two of the participants were able to and/or attempted to reassemble all of the refined functional blocks into a complete concept model, and only three participants mentioned that they thought a prototype could be 'Part of a complete design.' For many, this created additional challenges that they did not anticipate at the component level. Participant 6, who performed in accordance with this best practice behavior, successfully reassembled functional blocks and described how the team realized that they had not taken the system level challenges into consideration when refining at the component level: 'So once we put it together… on paper, in CAD, we have these tight tolerances. We actually had to put it together and take it apart and put it together several, several times to get everything to fit just right.'

Participant 13, on the other hand, who performed at the novice level, explained what happened when the team assembled their final model: 'We had expectations for the physical model to work, which it did, I mean, like without the spring. We had expectations that the circuitry components would work, and the code would work. But when we put it together, that's when it got tricky.' She continued: 'Once we built it, we noticed all these things that were kind of wrong with the design or needed to be modified.' (Participant 13).

Likewise, Participant 10, who also performed at the novice level, acknowledged that his prototyping activities were incomplete, even though he was able to construct a functional model: 'It could be said to make another physical prototype, and it would certainly help address a couple of things like comfort, locking mechanism, just the stability of the [prototype].'

Other low frequency activities included: 'Develop prototypes of multiple concepts in parallel' and 'Vary the scale of prototypes,' and were not mentioned initially when students shared their conceptions of prototypes. Only five participants reported the creation of multiple concepts outside of the idea generation and concept selection phases at an advanced level, but Participant 11, who performed in accordance with this best practice behavior, explained how he provided stakeholders with multiple prototypes at the same time, asking specific questions and gathering information that led to the development and refinement of ideas: 'The method that we used to gather information, the observing and asking questions because we had the prototypes that fed into idea generation.' Only three participants realized that a scaled up or down version of a model could indeed simplify the fabrication process and reported engaging in 'Vary the scale of the prototype.' Participant 8, who performed in accordance with this best practice behavior, described how she developed both a partial full-scale model as well as a complete scale model to learn different things: 'Then our other prototype, which we started referring to as the mockup, was a scaled-down mockup of the entire [model].'

3 Discussion

3.1 Participants' conceptions of prototypes

Participants' definitions of prototypes early in the interview were limited. In few cases were their definitions as broad and refined as how they later reported actually using prototypes during their recent project-based engineering design courses. For example, only three participants mentioned early on that prototypes could be used for communication, yet all participants reported using prototypes as tools to communicate ideas throughout their project. And though none of the teams produced a completely finished model of their design by the end of the semester, only six participants articulated that prototypes could be unfinished models, or works in progress.

Even fewer — only two participants — defined prototypes as non-physical models such as sketches and CAD models, but all participants reported the use of sketches, especially in the early phases of their projects, and all participants mentioned that they built CAD models of their design. Similarly, only three participants mentioned that a prototype could consist only of components of a complete design, but most participants reported that they produced partial prototypes to test and evaluate their design.

While only half of the participants stated that prototypes could be used for testing purposes as well as to demonstrate form and function, all participants claimed later to have used prototypes for testing and evaluation, and the majority said that they used prototypes to demonstrate form and function. And finally, only three participants conceptualized prototypes as tools to move a project through the individual design phases, yet when later describing their actual design projects, almost all participants mentioned they used prototypes in this way.

These limited initial definitions suggest that participants were not always aware of their own broad range of prototype usage, and that they, similar to findings of other studies, might not have intentionally planned for how they used prototypes (Atman et al., 2007; Camburn, Dunlap, Kuhr, et al., 2013; Camburn et al., 2015; Christie et al., 2012, pp. 1154—1122; Lande & Leifer, 2009; Yang & Epstein, 2005). Only upon detailed reflection on their projects, prompted by the interviewer, did participants realize the frequency and spectrum of their own prototype usage. This does not necessarily suggest misconceptions by the participants; rather, it may indicate that participants did not yet fully conceptualize the value and broad uses of prototypes. This is also supported by research on the value of repeated reflective practice in informing design behaviors and conceptions of design practices (Schön, 1984, 1992).

3.2 Participants' reported use of prototypes

All participants reported using prototypes to 'Test and evaluate.' The high frequency nature of this behavior might have been attributed to course structure, as participants were required to test their concepts and justify how their ideas solved the design problem (Dieter & Schmidt, 2012). On the other hand, ''Use prototypes to communicate' was not a required activity, but all participants reported using prototypes for this purpose. Participants found that communication improved in the presence of prototypes when reflecting on their projects, but did not mention this when giving their initial conceptions of prototype.

Similarly, while 15 novice designers reported using prototypes to iteratively refine their design problem definitions, these iterations occurred unexpectedly when participants experienced setbacks as the result of a trial-and-error approach or not prototyping intentionally. This also aligns well with findings and recommendations of studies on the benefits of reflective practice (Nokes et al., 2010; Popovic, 2004; Schön, 1984) and indicates that even after completing a project-based engineering design course, novice designers might not have yet developed the knowledge structures that enable them to quickly recognize large chunks of domain-relevant information (Chase & Simon, 1973, 1988) and determine suitable strategies and procedures for problem solving, including the use of prototypes.

Few novice designers reported using prototypes to define user requirements and engineering specifications. In contrast to design experts, who use prototypes early in a project to engage with stakeholders, novice designers primarily reported using prototypes with stakeholders later in the design process to share their progress and gather feedback. This echoes studies that have found that novice designers spend less time scoping a problem and do not seek the same depth and breadth of information prior to developing design solutions (Atman et al., 2007; Häggman et al., 2015; Mohedas, Daly, & Sienko, 2014b; Viswanathan, Atilola, Goodman, et al., 2014; Yang & Epstein, 2005). This lack of engagement with stakeholders early in the design process represents a missed opportunity and has the potential to negatively impact design outcomes.

3.3 Participants' behaviors in the context of prototyping best practices

Even though novices reported to have engaged in many of the prototyping best practice behaviors to some degree, many of their behaviors lacked intentionality, quality and frequency. They often did not use prototypes strategically in ways design experts do, resulting in the under-realization of many benefits prototyping can provide, and indicating the potentially limited retention of the benefits they did experience (Christie et al., 2012, pp. 1154–1122; Crismond & Adams, 2012; Hilton et al., 2015; Kelley, 2007; Kelley & Littman, 2006; Schrage, 2013; Viswanathan, Atilola, Goodman, et al., 2014; Webber et al., 2016).

We recorded the most disparity within a single prototyping best practice behavior for 'Use inexpensive prototypes early and efficiently.' This 'quick-and-dirty' prototyping best practice was evenly split: Half of the participants performed at the lowest level for this behavior and almost all of the remaining participants performed at the highest level. In addition to verbal descriptions, some participants mentioned that they used sketches as a more precise way of communicating their concepts to stakeholders. Although sketches can indeed provide more information than the verbal description of an idea alone, expert designers recognize that sketches can be ambiguous and vague, often omitting some information while highlighting or distorting other information (Tversky et al., 2003). The suggestive nature of sketches promotes their use primarily during idea generation and concept development rather than verification later in the project (Kelley, 2007; Yock et al., 2015). Here, too, we observed a prototyping best practice behavior, i.e., the use of sketches, with some participants, but novices may lack the skills and insight to fully recognize the benefits and shortcomings of this practice.

While 12 out of 16 participants engaged in 'Identify, prioritize and isolate functional blocks of prototypes,' only two participants engaged in the closely linked behavior, 'Reassemble blocks into complete concept models,' making this the reported lowest used prototyping best practice behavior overall. This critical step might have been reported at such low frequency because participants did not expect their prototypes to reveal design flaws at the component level or did not anticipate additional challenges when reassembling the individual, refined blocks. The limited amount of time available during a semester-long course, limited resources, as well as varying degrees of personal skills likely contributed to this low use, but also reflect realistic constraints that designers might experience in a professional environment outside the classroom (Kelley & Littman, 2006; Otto & Wood, 2000; Schrage, 2013).

4 Limitations and future work

One study limitation was the number of participants. Because of the small sample size, our findings might not be generalizable, but qualitative research aims for depth and transferability rather than generalizability (Daly et al., 2013; Marshall, 1996; Patton, 2014). In this exploratory study, we developed an understanding of participants' underlying reasons and motivations for using prototypes, provided detailed descriptions of our participants' actions, and described the research context and the assumptions made (Patton, 2014; Whittemore, Chase, & Mandle, 2001). The nature of the project and the structure of the course, as well as resources and fabrication skills of the participants are likely to have influenced their choice of prototyping behavior. Therefore, our findings may not be representative of courses or disciplines outside of engineering. Thus, while our results may not be generalizable, they do provide a baseline for future research.

The study did not consider the demographics of the participants, and future work could examine differences that might exist between groups of participants as well as other factors that might influence design performance. A third limitation is that we did not directly observe how participants actually used prototypes. Instead, we relied on their self-reported prototyping activities. Future work might include direct observation of prototyping behaviors throughout the entire design project. Next, the review of the literature on prototyping best practices was limited to prominent textbooks in design. A more systematic review, including research on expert best practice behaviors for using prototypes, could be included in future work. It is important to recognize that the prototyping best practices identified in this study might not be appropriate for all design problems or contexts. Therefore, some reported underutilization might have been caused by a particular behavior not aligning well with a project (like 'vary the scale of a prototype'), which could have influenced our findings. Furthermore, future research could examine the extent to which expert designers follow the prototyping best practices we identified from prominent textbooks to determine the impact of these best practices on design outcomes.

5 *Implications for design practice*

This study points to several areas that might serve as focal points for further research, for design practice as well as for engineering education. Novice designers could be taught to be specific in their prototyping practice, meaning they learn how to use prototypes strategically, to answer particular questions. For example, developing user requirements and translating these requirements into engineering specifications were some of the most difficult activities mentioned by participants, and both are essential steps in the process of designing a successful product. Novice designers could be encouraged to iteratively use prototypes to refine a selected concept not only until the technical specifications are met, but also until real-world user requirements have been considered through engagements with stakeholders. This might include feedback about how a device feels in the end user's hand during actual use and might lead the designer to additional design requirements beyond the initial specifications (Kelley, 2007; Yock et al., 2015). Additional support and time allocated by instructors might be needed to encourage novice designers to use such an iterative approach in which each prototype builds on what has been learned from the previous design iteration.

Next, the findings from this and related future research might facilitate more reflective practice when it comes to prototyping. Participants in this study reported using prototypes in ways that aligned with prototyping best practices, but they often did not recognize that they were utilizing these methods, even after personally having experienced the benefits. When prompted by the interviewer to reflect on their process, participants reported using prototypes more frequently, and for additional purposes, than they had initially claimed. They also recognized that their projects would have benefitted from an increased use of prototypes, particularly during the early phases of their design process and specifically, to facilitate engagement with stakeholders. Even within the constraints of a semester-long design course, opportunities might still exist to leverage prototypes more broadly. Further and repeated prototyping exposure along with a prescriptive design process, explicit discussion, and guided reflection might help novices translate their experiences into concrete knowledge and develop their own knowing-in-action habits (Dreyfus & Dreyfus, 1980; Nokes et al., 2010; Popovic, 2004; Schön, 1984).

Third, this work points to the need to support more intentionality when it comes to novice use of prototypes. When comparing the reported behaviors to prototyping best practice, a lack of intentionality with novice designers surfaced. The limited knowledge structures and experience likely contributed to this underutilization of prototypes, and the reported activities were often a response to a course requirement. In comparison, prototyping best practices suggest that designers ask specific questions that they then try to answer with the help of prototypes (Camburn et al., 2015; Camburn, Dunlap, Kuhr, et al. 2013). To support novice designers in leveraging prototypes, whether in an academic setting or design training in professional practices, an instructor could ask for questions to be developed prior to building prototypes.

Additionally, prototypes could be developed during several phases and made a deliverable of the project that novice designers present periodically to show progress in their development. This could be in the form of individual phase deliverables or a restructured course outline in which prototypes become an integral part of the design process. Since students are often pressed for time during their projects, the addition of iteratively using prototypes as deliverables in various phases needs to be carefully evaluated. Stanford, Georgia Tech and the University of Michigan already execute capstone design courses that last a full academic year and leverage multiple prototyping opportunities, representing a commitment of not insignificant resources by the institutions (Dym, Agogino, Eris, Frey, & Leifer, 2005; Sienko, Kaufmann, Musaazi, Sarvestani, & Obed, 2014).

Lastly, design researchers might use these findings to broaden their understanding of the impact that prototypes can have on communication among designers within their team as well as between designers and stakeholders. As many design projects today include a variety of people with often diverse backgrounds, an effective way of communicating design intent is paramount. This diversity might not only occur within a design team in industry or academia; an increased number of products designed for a global market also introduce more geographically diverse stakeholder groups. This in turn introduces additional communication challenges, and prototypes can play an essential part in overcoming such obstacles.

6 Conclusions

We found that novice designers' conceptions of prototypes varied widely from one another and were consistently more limited in scope than how participants later described using prototypes during their most recent project-based engineering design courses. Even though novice designers engaged in all prototyping best practice behaviors we evaluated to some extent, they did so infrequently, mostly unintentionally, and without a structured approach. Their use of prototypes was limited throughout the design process, but specifically during the early stages when user requirements and specifications were being defined. When reflecting on their projects however, participants recognized the importance of using prototypes during all phases of the engineering design process and in particular, to engage with stakeholders. The limited definitions and uses of prototypes do not necessarily suggest misconceptions by participants, but that novice designers might not have yet developed a rich understanding of the values of prototypes. Novice designers might therefore benefit from a more prescriptive and reflection-based design process as well as additional, iterative prototyping experiences, including engaging with stakeholders, especially during the front-end phases of the design process.

Acknowledgements

Research reported in this publication was supported by the Fogarty International Center of the U. S. National Institutes of Health under award number 1D43TW009353 and by the University of Michigan's Investigating Student Learning Grant, 2016, funded by the Center for Research on Learning and Teaching, the Office of the Vice Provost for Global and Engaged Education and the College of Engineering. The research team would like to express their gratitude to Professors Elsie Effah Kaufmann, Karin Martin and Alexandra Murphy for their advice and Kimberlee Roth for her help with editing. We also thank Tian Bao, Vincent Barone, Catherine Kinnaird, Ibrahim Mohedas, and Maria Young for their input and feedback, and the *Design Studies* reviewers for their helpful comments.

Appendix A Codes and rating criteria for deductive coding

Best Practice	*Definition*	*0 — little or no evidence of the behavior*	*1 — some evidence of an intermediate behavior*	*2 — evidence that behavior aligned with best practice*
Design the minimal model needed.	Only what is needed to answer one or more question(s) is prototyped, leaving off unnecessary features.	Created the full model, and did not focus on only what was needed.	Created more than what was needed to answer specific question(s), and did include unnecessary features.	Created only what was needed to answer specific question(s), and did not include unnecessary features.
Develop prototypes of multiple concepts in parallel.	Multiple concepts are prototyped in parallel to help with the selection of the most promising approach.	Created none or only one prototype at a time.	Created multiple prototypes but not in parallel, and not to aid with the selection of the most promising approach.	Created multiple prototypes in parallel to help with the selection of the most promising approach.
Identify, prioritize and isolate functional blocks of prototype(s).	Features (functional, aesthetic, etc.) that need to be prototyped are determined.	Did not identify, prioritize and isolate functional blocks of prototype(s).	Identified only an individual functional block, did not prioritize, isolate or missed functional blocks.	Identified, prioritized and isolated multiple functional blocks.
Reassemble functional blocks into complete concept model(s).	Re-integrate what has been learned from the functional blocks into the whole concept model(s).	Did not reassemble functional blocks into complete concept model(s).	Reassembled some functional blocks into complete concept model(s).	Reassembled all functional blocks into complete concept model(s).
Use appropriate prototype format(s) to address specific design question(s).	Select the best-suited prototype format to address specific question(s).	Used only one prototype format.	Used multiple prototype format(s), but did not explain why format was chosen, or chose because format was readily available.	Selected the format best suited to address specific question(s), and explicitly stated the reason for choosing format(s).
Use inexpensive prototypes early and efficiently.	Simple and inexpensive concept models are built to gain additional information (trial and error prototyping).	Did not use simple and inexpensive prototypes early.	Used one simple and inexpensive prototype early.	Intentionally constructed multiple simple and inexpensive prototypes early.
Use prototyping iteratively and develop increasingly refined prototypes.	Prototypes are increasingly refined and incorporate knowledge gained from previous prototype(s).	Did not refine or incorporate additional knowledge into prototype(s).	Made refinements and considered incorporation of knowledge into prototype(s).	Made major refinements to prototype(s), and incorporated some knowledge gained from previous prototype(s).

(*continued on next page*)

(*continued*)

Best Practice	*Definition*	*0 — little or no evidence of the behavior*	*1 — some evidence of an intermediate behavior*	*2 — evidence that behavior aligned with best practice*
Use prototypes to answer specific design questions.	One or more specific question(s) is/are identified and one or more specific prototype(s) is/are created to find the answer.	Built prototype(s) for other reasons (i.e., required deliverable).	Created prototype(s) to gather general feedback (i.e., did not have one or more specific question(s) in mind).	Created prototype(s) to gather feedback on one or more specific question(s) (i.e., size, weight, etc.).
Use prototypes to communicate design concepts.	Prototypes are used to communicate ideas to team members and stakeholders.	Did not use prototype(s) to communicate design concepts or ideas.	Unintentionally or accidentally used prototype(s) for communication with teammates or stakeholders (e.g., prototype(s) was/were readily accessible and therefore used).	Intentionally used prototype(s) for communication, both with teammates and stakeholders.
Use prototypes to define design problem(s).	Early use of prototypes leads to development of design requirements and specifications.	Did not use prototype(s) to define design problem(s).	Unintentionally or non-specifically used prototype(s) to define design problem(s).	Intentionally used prototype(s) to define design problem(s).
Use prototypes to engage with stakeholders.	Prototypes are used to engage with stakeholders.	Did not use prototypes to engage with stakeholders.	Used prototypes to engage with stakeholders to show progress and obtain general feedback.	Used prototypes intentionally to engage with stakeholders to obtain specific feedback.
Use prototypes to refine design problem definition(s).	Used prototype(s) after problem definition phase to refine design requirements and specifications.	Did not use prototype(s) after problem definition phase to refine design requirements and specifications.	Used prototype(s) unintentionally or non-specifically but implemented feedback received to refine design problem definition(s).	Used prototype(s) intentionally to gather feedback to refine design problem definition(s).
Use prototypes to test concepts.	Prototypes are used to test a concept or idea.	Did not use prototype(s) to test a concept or idea.	Used prototype(s) to test parts or elements of the concept or idea.	Used prototype(s) to test individual parts or elements as well as the whole design concept.
Use readily accessible and applicable existing objects or combinations of objects as prototypes.	Existing products or parts are utilized and/or incorporated into a prototype.	Did not reference existing product(s) as prototype(s).	Unintentionally used existing product(s) to gather feedback (e.g., 'Would the handle from this product work on the new design?').	Intentionally used or incorporated existing product(s), part(s) or mechanism(s) into prototype(s), or modified existing product(s) to create new prototype(s).
Vary the scale of prototype(s).	The scale of a prototype(s) is/are adjusted when appropriate to make construction easier.	Did not vary the scale of prototype(s) or feature(s).	Varied the scale of an individual feature or element of the prototype(s).	Varied the scale of multiple features or elements, including scaling of the full prototype(s).

References

Adams, R. S., Daly, S. R., Mann, L. M., & Dall'Alba, G. (2011). Being a professional: Three lenses into design thinking, acting, and being. *Design Studies, 32*(6), 588–607. http://dx.doi.org/10.1016/j.destud.2011.07.004.

Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design, 14*(1), 1–11. http://dx.doi.org/10.1007/s00163-002-0023-z.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359–379. http://dx.doi.org/10.1002/j.2168-9830.2007.tb00945.x.

Ball, L. J., & Ormerod, T. C. (2000). Putting ethnography to work: The case for a cognitive ethnography of design. *International Journal of Human-computer Studies, 53*(1), 147–168. http://dx.doi.org/10.1006/ijhc.2000.0372.

Björklund, T. A. (2013). Initial mental representations of design problems: Differences between experts and novices. *Design Studies, 34*(2), 135–160. http://dx.doi.org/10.1016/j.destud.2012.08.005.

Boyatzis, R. E. (1998). *Transforming qualitative Information: Thematic analysis and code development* (1st edn).. Thousand Oaks, CA: SAGE Publications, Inc.

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies, 9*(3), 159–168. http://dx.doi.org/10.1016/0142-694X(88)90045-2.

Camburn, B., Dunlap, B., Gurjar, T., Hamon, C., Green, M., Jensen, D., …, & Wood, K. (2015). A systematic method for design prototyping. *Journal of Mechanical Design, Transactions of the ASME, 137*(8). http://dx.doi.org/10.1115/1.4030331.

Camburn, B. A., Dunlap, B. U., Kuhr, R., Viswanathan, V. K., Linsey, J. S., Jensen, D. D., …, & Wood, K. L. (2013). *Methods for prototyping strategies in conceptual phases of Design: Framework and experimental assessment, V005T06A033*. http://dx.doi.org/10.1115/DETC2013-13072.

Camburn, B. A., Dunlap, B. U., Viswanathan, V., Linsey, J. S., Jensen, D. D., Crawford, R. H., …, & Wood, K. L. (2013). *Connecting Design Problem Characteristics to Prototyping Choices to Form a Prototyping Strategy*.

Cash, P., Elias, E., Dekoninck, E., & Culley, S. (2012). Methodological insights from a rigorous small scale design experiment. *Design Studies, 33*(2), 208–235. http://dx.doi.org/10.1016/j.destud.2011.07.008.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology, 4*(1), 55–81. http://dx.doi.org/10.1016/0010-0285(73)90004-2.

Chase, W. G., & Simon, H. A. (1988). The mind's eye in chess. In *Readings in cognitive science* (pp. 461–494). Elsevier.

Christie, E. J., Jensen, D. D., Buckley, R. T., Menefee, D. A., Ziegler, K. K., Wood, K. L., & Crawford, R. H. (2012). Prototyping strategies: Literature review and identification of critical variables. In *American Society for Engineering Education*. American Society for Engineering Education.

Clark, K. B., & Fujimoto, T. (1991). *Product development performance: Strategy, organization, and management in the world auto industry*. Harvard Business Press.

Crabtree, B., & Miller, W. (1992). A Template approach to text analysis: Developing and using codebooks. *Doing Qualitative Research in Primary Care: Multiple Strategies* 93–109.

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th edn.). Thousand Oaks: SAGE Publications, Inc.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies, 38*, 54–91. http://dx.doi.org/10.1016/j.destud.2015.01.002.

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738–797. http://dx.doi.org/10.1002/j.2168-9830.2012.tb01127.x.

Cross, N. (2004). Expertise in design: An overview. *Design Studies, 25*(5), 427–441. http://dx.doi.org/10.1016/j.destud.2004.06.002.

Cross, N. (2007). *Designerly ways of knowing* (1 edition).. Basel; London: Birkhäuser Architecture.

Daly, S. R., Adams, R. S., & Bodner, G. M. (2012). What does it mean to design? A qualitative investigation of design professionals' experiences. *Journal of Engineering Education, 101*(2), 187–219.

Daly, S. R., McGowan, A., & Papalambros, P. (2013). Using qualitative research methods. In *19th International Conference on Engineering Design*.

Daly, S. R., & Yilmaz, S. (2015). Directing convergent and divergent activity through design feedback. *Analyzing Design Review Conversation, 21*, 413–429.

De Beer, D. J., Campbell, R. I., Truscott, M., Barnard, L. J., & Booysen, G. J. (2009). Client-centred design evolution via functional prototyping. *International Journal of Product Development, 8*(1), 22–41. http://dx.doi.org/10.1504/IJPD.2009.023747.

Dieter, G., & Schmidt, L. (2012). *Engineering design* (5th edn).. New York: McGraw-Hill Education.

Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., & Klemmer, S. R. (2010). Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. *ACM Transactions on Computer-human Interaction, 17*(4), 1–24. http://dx.doi.org/10.1145/1879831.1879836.

Dreyfus, S. E., & Dreyfus, H. L. (1980). *A five-stage model of the mental activities involved in directed skill acquisition*. Berkeley: Operations Research Center, University of California.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education, 94*(1), 103–120. http://dx.doi.org/10.1002/j.2168-9830.2005.tb00832.x.

Ertas, A., & Jones, J. C. (1996). *The engineering design process* (2nd edn).. New York: Wiley.

Gerber, E. (2009). *Prototyping: Facing uncertainty through small wins*. DS 58-9: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 9, Human Behavior in Design, Palo Alto, CA, USA, 24.-27.08.2009.

Goldschmidt, G. (2007). To see eye to eye: The role of visual representations in building shared mental models in design teams. *CoDesign, 3*(1), 43–50. http://dx.doi.org/10.1080/15710880601170826.

Häggman, A., Tsai, G., Elsen, C., Honda, T., & Yang, M. C. (2015). Connections between the design tool, design attributes, and user preferences in early stage design. *Journal of Mechanical Design, 137*(7), 71408.

Hamon, C. L., & Green, M. G. (2014). Virtual or physical prototypes? Development and testing of a prototyping planning tool. In *121st ASEE Annual Conference & Exposition*.

Hilton, E., Linsey, J., & Goodman, J. (2015). Understanding the prototyping strategies of experienced designers. In *IEEE Frontiers in Education Conference*

(FIE), 2015. 32614 2015 (pp. 1–8). http://dx.doi.org/10.1109/FIE.2015.7344060.

Ho, C. H. (2001). Some phenomena of problem decomposition strategy for design thinking: Differences between novices and experts. *Design Studies, 22*(1), 27–45.

Houde, S., & Hill, C. (1997). What do prototypes prototype. *Handbook of Human-Computer Interaction, 2*, 367–381.

Kelley, T. (2007). *The art of innovation: Lessons in creativity from IDEO, America's leading design firm*. Crown Publishing Group.

Kelley, T., & Littman, J. (2006). *The ten faces of innovation: IDEO's strategies for defeating the devil's advocate and driving creativity throughout your organization*. Crown Publishing Group.

Knapp, J., Zeratsky, J., & Kowitz, B. (2016). *Sprint: How to solve big problems and test new ideas in just five days*. Simon and Schuster.

Koen, P. A., Ajamian, G. M., Boyce, S., Clamen, A., Fisher, E., Fountoulakis, S., …, & Seibert, R. (2002). *Fuzzy front end: Effective methods, tools, and techniques*. New York, NY: Wiley.

Kordon, F., & Luqi. (2002). An introduction to rapid system prototyping. *IEEE Transactions on Software Engineering, 28*(9), 817–821. http://dx.doi.org/10.1109/TSE.2002.1033222.

Kudrowitz, B. M., & Wallace, D. (2013). Assessing the quality of ideas from prolific, early-stage product ideation. *Journal of Engineering Design, 24*(2), 120–139. http://dx.doi.org/10.1080/09544828.2012.676633.

Lande, M., & Leifer, L. (2009). Prototyping to learn: Characterizing engineering students' prototyping activities and prototypes. In *DS 58-1: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 1, Design Processes, Palo Alto, CA, USA, 24-27.08. 2009*.

Lawson, B. (1994). *Design in mind*. Oxford England; Boston: Architectural Press.

Marshall, M. N. (1996). Sampling for qualitative research. *Family Practice, 13*(6), 522–526. http://dx.doi.org/10.1093/fampra/13.6.522.

Miller, W. S., & Summers, J. D. (2012). Investigating the use of design methods by capstone design students at Clemson University. *International Journal of Technology and Design Education, 23*(4), 1079–1091. http://dx.doi.org/10.1007/s10798-012-9227-3.

Moe, R. E., Jensen, D. D., & Wood, K. L. (2004)*Prototype partitioning based on requirement flexibility, Vol. 2004*. ASME 65–77. http://dx.doi.org/10.1115/DETC2004-57221.

Mohedas, I., Daly, S. R., & Sienko, K. H. (2014a). Design ethnography in capstone design: Investigating student use and perceptions. *International Journal of Engineering Education, 30*(4), 888–900.

Mohedas, I., Daly, S. R., & Sienko, K. H. (2014b). Gathering and synthesizing information during the development of user requirements and engineering specifications. In *121st ASEE Annual Conference & Exposition, Indianapolis, IN, June* (pp. 15–18).

Mohedas, I., Daly, S. R., & Sienko, K. H. (2014c). Student use of design ethnography techniques during front-end phases of design (p. 24.1126.1-24.1126.9). In *Presented at the 2014 ASEE Annual Conference & Exposition*.

Mohedas, I., Daly, S. R., & Sienko, K. H. (2015). Requirements development: Approaches and behaviors of novice designers. *Journal of Mechanical Design, 137*(7), 071407.

Mohedas, I., Daly, S. R., & Sienko, K. H. (2016). Use of skill acquisition theory to understand novice to expert development in design ethnography. *International Journal of Engineering Education, 32*(3), 1364–1371.

Mohedas, I., Sabet Sarvestani, A., Daly, S. R., & Sienko, K. H. (2015). Applying design ethnography to product evaluation: A case example of a medical device in a low-resource setting. In *DS 80-1 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 1: Design for Life, Milan, Italy, 27-30.07. 15*.

Nokes, T. J., Schunn, C. D., & Chi, M. (2010). *International encyclopedia of education*. Presented at the Elsevier Ltd. http://dx.doi.org/10.1016/B978-0-08-044894-7.00486-3.

Otto, K., & Wood, K. (2000). *Product Design: Techniques in reverse engineering and new product development* (1st edn).. Upper Saddle River, NJ: Pearson.

Ozkan, O., & Dogan, F. (2013). Cognitive strategies of analogical reasoning in design: Differences between expert and novice designers. *Design Studies, 34*(2), 161−192. http://dx.doi.org/10.1016/j.destud.2012.11.006.

Patton, M. Q. (2014). *Qualitative research & evaluation methods: Integrating theory and practice*. SAGE Publications.

Popovic, V. (2004). Expertise development in product design—strategic and domain-specific knowledge connections. *Design Studies, 25*(5), 527−545. http://dx.doi.org/10.1016/j.destud.2004.05.006.

Schön, D. A. (1984). *The reflective practitioner: How professionals think in action*. Basic Books.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. *Knowledge-based Systems, 5*(1), 3−14.

Schrage, M. (2013). *Serious play: How the world's best companies simulate to innovate*. Harvard Business Press.

Scott, J. B. (2008). The practice of usability: Teaching user engagement through service-learning. *Technical Communication Quarterly, 17*(4), 381−412. http://dx.doi.org/10.1080/10572250802324929.

Sienko, K. H., Kaufmann, E. E., Musaazi, M. E., Sarvestani, A. S., & Obed, S. (2014). Obstetrics-based clinical immersion of a multinational team of biomedical engineering students in Ghana. *International Journal of Gynecology and Obstetrics, 127*(2), 218−220. http://dx.doi.org/10.1016/j.ijgo.2014.06.012.

Skaggs, P. (2010). Ethnography in product design-looking for compensatory behaviors. *Journal of Management and Marketing Research, 3*, 1.

Stempfle, J., & Badke-Schaub, P. (2002). Thinking in design teams − an analysis of team communication. *Design Studies, 23*(5), 473−496. http://dx.doi.org/10.1016/S0142-694X(02)00004-2.

Sugar, W. A. (2001). What is so good about user-centered design? Documenting the effect of usability sessions on novice software designers. *Journal of Research on Computing in Education, 33*(3), 235−250. http://dx.doi.org/10.1080/08886504.2001.10782312.

Tversky, B., Suwa, M., Agrawala, M., Heiser, J., Stolte, C., Hanrahan, P., …, & Haymaker, J. (2003). Sketches for design and design of sketches. In *Human Behaviour in Design* (pp. 79−86). Springer Berlin Heidelberg.

Ullman, D. G., Wood, S., & Craig, D. (1990). The importance of drawing in the mechanical design process. *Computers & Graphics, 14*(2), 263−274.

Viswanathan, V. K. C. (2012). *Cognitive effects of physical models in engineering idea generation*. (Doctoral dissertation, Texas A&M University).

Viswanathan, V., Atilola, O., Esposito, N., & Linsey, J. (2014). A study on the role of physical models in the mitigation of design fixation. *Journal of Engineering Design, 25*(1−3), 25−43. http://dx.doi.org/10.1080/09544828.2014.885934.

Viswanathan, Atilola, Goodman, & Linsey. (2014). Prototyping: A key skill for innovation and life-long learning. In *2014 IEEE Frontiers in Education*

Conference (FIE) Proceedings (pp. 1–8). http://dx.doi.org/10.1109/FIE.2014.7044423.

Viswanathan, & Linsey, J. S. (2009). Enhancing student innovation: Physical models in the idea generation process. In *2009 39th IEEE Frontiers in Education Conference* (pp. 1–6). http://dx.doi.org/10.1109/FIE.2009.5350810.

Wang, G. G. (2003). Definition and review of virtual prototyping. *Journal of Computing and Information Science in Engineering, 2*(3), 232–236. http://dx.doi.org/10.1115/1.1526508.

Webber, F. C., Schafer, K. H., Vinande, E. T., McIntire, J. P., Jensen, D. D., Foong, S., …, & Wong, G. H. (2016). Singapore-U.S. Tactical All-Inclusive Navigation (SUSTAIN) collaborative innovation. In *Presented at the 2016 ASEE International Forum*.

Whittemore, R., Chase, S. K., & Mandle, C. L. (2001). Validity in qualitative research. *Qualitative Health Research, 11*(4), 522–537.

Yang, M. C. (2009). Observations on concept generation and sketching in engineering design. *Research in Engineering Design, 20*(1), 1–11. http://dx.doi.org/10.1007/s00163-008-0055-0.

Yang, M. C., & Epstein, D. J. (2005). A study of prototypes, design activity, and design outcome. *Design Studies, 26*(6), 649–669. http://dx.doi.org/10.1016/j.destud.2005.04.005.

Yilmaz, S., & Seifert, C. M. (2011). Creativity through design heuristics: A case study of expert product design. *Design Studies, 32*(4), 384–415. http://dx.doi.org/10.1016/j.destud.2011.01.003.

Yock, P. G., Zenios, S., Makower, J., Brinton, T. J., Kumar, U. N., Watkins, F. T. J., …, & Kurihara, C. (2015). In *Biodesign: The Process of Innovating Medical Technologies* (2nd edn).. Cambridge University Press.

Zemke, S. C. (2012). Student Learning in Multiple Prototype Cycles (p. 25.1185.1-25.1185.12). In *Presented at the 2012 ASEE Annual Conference & Exposition*.