Informing Intentional Use of Prototyping in Engineering Design: Context-Specific Novice Approaches and Stakeholder Feedback

by

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Abstract

Prototypes are essential tools that can be used strategically throughout the design process to increase the likelihood that a product achieves stakeholder needs. Prototyping allows physical or visual form to be given to an idea, and research has shown that prototypes have the potential to support communication and improve product requirements elicitation and design input by enabling stakeholders and designers to engage around a "shared space" – the prototype.

Despite the numerous benefits of using prototypes throughout a design process, novice designers often limit their use of prototypes to test and verify a chosen concept during the later phases of their processes. Limited studies to date have investigated novice uses of prototypes during the front-end phases of design and the effects of context, stakeholder type, and prototype type on stakeholder feedback. This research leverages approaches from multiple disciplines to characterize 1) novice designers' uses of prototypes and 2) the effects of various factors on stakeholder design input during engagement with prototypes.

We conducted interviews with engineering design students in different contexts to investigate their use of prototypes. We also developed a prototyping best practice framework to evaluate the intentionality in novice designers' use of prototypes during design. To deepen our understanding of how prototype type can influence stakeholder feedback, we presented various prototypes of a medical device concept to diverse stakeholders, including medical doctors, medical students and nurses and asked questions to elicit feedback on the design.

Research findings indicated that novice designers lacked intentionality when using prototypes. Their prototyping behaviors often occurred unintentionally to satisfy course

requirements or as a response to failure or setbacks. Novice designers from different contexts favored different prototype types, and all participants underutilized prototypes, particularly during the front-end phases of design and when engaging with stakeholders. Our results further showed that nuances like prototype type, stakeholder group, and question type influenced the quality of stakeholder feedback.

Since variation in prototype type, stakeholder group, and question type had a significant effect on the quality of stakeholder feedback, and since most novice designers did not use prototypes intentionally, our findings point to missed opportunities that likely impact several areas: what novice designers learn about using prototypes, the prototyping practices with which they begin professional practice, and ultimately the human-centered design solutions they create.

This research leveraged, and has implications for, engineering design, design education, industrial design, design science, and design research methods. We expect that some of our findings, specifically that 1) novice designers lacked intentionality and underutilized prototypes, and 2) the types of prototypes, stakeholders, and questions influenced stakeholder feedback, are transferable to, and can have a broader impact on, other contexts in which prototypes are used. The fact that novice designers lacked intentionality in prototype use suggests that repeated and reflective practice is needed and informs pedagogical and industrial approaches throughout the engineering education and practice spectrum. We recommend that educators encourage a broader, more frequent use of prototypes during engineering design processes. By doing so, novice designers can develop the knowledge structures necessary to use prototypes intentionally, and intentionally with stakeholders, during design.

Chapter 1 Introduction, background and motivation

1.1 Introduction and background

“The soul never thinks without an image.” – *Aristotle*

1.1.1 Defining prototypes and their uses

Prototypes are essential tools in a design process (Viswanathan, Atilola, Goodman, & Linsey, 2014; Yang & Epstein, 2005) that allow physical or virtual form to be given to an idea (Kelley & Littman, 2006; Schrage, 1999). While prototypes are often thought of as tangible, three-dimensional models and sometimes existing objects, virtual prototypes like sketches and computer models are also considered prototypes (Hamon & Green, 2014; Ullman, Wood, & Craig, 1990).

Designers can use prototypes throughout a design process, and the type, as well as the level of refinement and complexity of a prototype typically change as a project progresses (Crismond & Adams, 2012; Hilton, Linsey, & Goodman, 2015). For example, while quick and simple prototypes like sketches and mock-ups are frequently used early, more refined and higher fidelity models are often used during later stages of the product development cycle (Baxter, 1995; Crismond & Adams, 2012; Hilton et al., 2015). Prototypes are often used to test and verify a function towards the end of the product development process (Dieter & Schmidt, 2012; Dym, Little, Orwin, & Spjut, 2009; Tayal, 2013). This includes a focus on technical and manufacturing details that are based on quality, performance, and cost of a part. These high-fidelity artifacts allow for validation of a chosen function and can require significant investment in resources, like machining or limited production run injection molding.

Regardless of design phase, prototypes may be created to investigate visual and aesthetic attributes of ideas (Christie et al., 2012; De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Hilton et al., 2015; Schrage, 1999; Viswanathan et al., 2014). Instead of creating fully functional prototypes, these models focus on human factors rather than functionality and testability.

Using a human-centered design approach, prototypes can be used to identify and define design problems, develop an understanding of user needs and requirements, and verify that a suggested solution solves the problem (De Beer et al., 2009; Kelley, 2007; Moe, Jensen, & Wood, 2004; Schrage, 1999; Viswanathan & Linsey, 2009; Yang & Epstein, 2005; Yock et al., 2015). Framing a problem from a stakeholder's perspective is essential for creating effective design solutions, and the established requirements can serve as tools against which to measure the proposed solution. Prototypes can also be created with a focus on communication that supports the sharing of ideas among team members as well as with stakeholders (Bogers & Horst, 2014; Buchenau & Suri, 2000; Goldschmidt, 2007; Mascitelli, 2000; Skaggs, 2010; Stempfle & Badke-Schaub, 2002; Terwiesch & Loch, 2004; Yang & Epstein, 2005). Here, prototypes can support communication around a shared object (Schrage, 1999) and have the potential to ensure that individuals have the same mental image of a product when engaging in a conversation (Goldschmidt, 2007).

Expert designers across disciplines recommend a "quick and simple" approach to prototyping (Brandt, 2007; Campbell et al., 2007; Gerber, 2009; Houde & Hill, 1997; Kelley, 2010) that supports the generation of several prototypes rapidly and enables iteration that can lead to increasingly refined models. This method allows for sharing, reviewing, and evaluating ideas through minimal viable products (Moogk, 2012) without investing much time and money, or what Houde and Hill (1997) call "sunk cost."

The iterative use of prototypes also enables designers to improve a concept by incorporating what they learned from previous iterations (Ulrich & Eppinger, 2015; Yang & Epstein, 2005). To achieve this, design experts tend to use prototypes at the component level instead of prototyping the entire product at once. Individual functional blocks are identified and worked on, making it easier to solve smaller chunks of a complex problem prior to reassembling into a complete model (Gerber, 2009; Hilton et al., 2015). Experienced practitioners often find it easier to face uncertainty this way, and research has shown that "small wins," i.e., achieving success at the component level, leads to more confidence and commitment by the designers, and ultimately project success (Gerber, 2009).

1.1.2 Types of prototypes

Prototypes come in a variety of forms. For example, in a study evaluating the usability of mobile devices, Lim et al. (2006) distinguished between low- and high-fidelity prototypes as factors that influenced participants' responses. Houde and Hill (1997) defined prototypes as "any representation of a design idea, regardless of medium," including preexisting objects that can be used to answer design questions. Houde and Hill suggest grouping prototypes according to what they represent, and developed a model that defines the dimensions of the prototype according to their role; look and feel; and implementation. In this model, each dimension is linked to specific questions, with "role" referring to the function of the prototype, "look and feel" referring to the sensory experience of the user, and "implementation" referring to its function and how the prototype actually works.

Ruecker (Ruecker, 2015) suggested three categories of prototypes in design and the digital humanities, which are intended for experiment, development, and provocation respectively, but also mentioned overlap between these categories. Ruecker also suggested considering the type of project prototypes are supporting. This includes production-driven prototypes that are intended for refinement until a final solution is found. The purpose of an experimental prototype is to produce generalized knowledge about an idea instead of a product. “Provotypes,” or provocative prototypes, are intended to challenge assumptions and understandings of participants to help define the boundaries of a possible solution space (Boer & Donovan, 2012; Boer, Donovan, & Buur, 2013; Ruecker, 2015).

Prototype type can vary by design context. For example, in design contexts where artifacts are two-dimensional, such as in user interface design and website design, prototypes are rarely physical models and instead include sketches, Post-it® notes, story boards, static screen images as well as functional websites that might compromise appearance, but include functional features like buttons and links (Walker, Takayama, & Landay, 2016). In contexts where artifacts are large in scale, such as architecture, prototypes are often scale models that do not represent the physical properties of the final product. This includes sketches and scale drawings (Fraser & Henmi, 1993) as well as physical models. These models can represent interior and or exterior features and details, and often include situational details like geographical setting and landscaping features. When architects want to share perceptions of a space, renderings or more recently, virtual reality models are created to give people an impression of what a space would look and feel like (Feiner, MacIntyre, Höllerer, & Webster, 1997).

1.1.3 Novice and expert use of prototypes

Through experience and reflective practice, many expert designers have developed both domain knowledge and structures that allow them to organize prior knowledge in ways that help them solve problems effectively (Chase & Simon, 1973, 1988). Similar to how chess players learn to recognize familiar patterns, expert designers are also able to identify similar circumstances and transfer prior knowledge to different contexts to solve new problems (Nokes, Schunn, & Chi, 2010).

Expert designers acquire these knowledge structures, or knowing-in-action, through reflective practice (Schön, 1984), but novice designers typically have not yet had similarly extensive experiences. Consequently, they are often unaware of useful prototyping practices that they could use to support their design efforts (Ahmed, Wallace, & Blessing, 2003; Björklund, 2013; Popovic, 2004).

Implicit in expert best practices for using prototypes throughout the design process, and in particular to engage stakeholders, is the iterative, intentional use of prototypes to achieve a purpose, often multiple purposes. In other words, they create prototypes to answer specific questions, and they select the most appropriate prototype format to get the information they need (Ahmed et al., 2003; Hilton et al., 2015; Popovic, 2004).

Novice designers often create prototypes to satisfy course requirements rather than developing prototypes intentionally to answer specific questions (Viswanathan et al., 2014). As a result, less experienced engineering designers tend to underutilize prototypes.

Several studies have shown that novices spend less time and resources on prototyping, use them in fewer phases, and for fewer activities during their design projects (Atman et al., 2007; Häggman, Tsai, Elsen, Honda, & Yang, 2015; Viswanathan et al., 2014). Novices commonly build prototypes toward the end of the design process to test their concepts rather than use them as tools throughout the process and to iterate on and refine their ideas (Hamon & Green, 2014; Lande & Leifer, 2009; Zemke, 2012).

Additionally, while studies have shown that novices often use simple prototypes like sketches and mockups during idea generation (Atman et al., 2007; Cardella, Atman, Turns, & Adams, 2008; Yang, 2009), they tend to underutilize prototypes during the earliest phases, when the problem is defined and user requirements and engineering specifications are established (Atman et al., 2007; Mohedas, Daly, & Sienko, 2014; Yang & Epstein, 2005).

1.1.4 Using prototypes during stakeholder engagement

Collecting and synthesizing design input requires stakeholder engagement (Kelley & Littman, 2006), but eliciting feedback from stakeholders is often challenging and can result in conflicting information (Mohedas, Daly, & Sienko, 2015). Good communication between designers and stakeholders is critical, and many experts agree that sharing ideas with stakeholders through prototypes rather than verbal descriptions alone is beneficial (Jensen, Elverum, & Steinert, 2017; Kelley & Littman, 2006; Scott, 2008). This is even more critical when designing at distance with limited access to stakeholders, or communicating with stakeholders from different professional, cultural and geographical backgrounds (Castillo, Diehl, & Brezet, 2012; Scrivener, Harris, Clark, Rockoff, & Smyth, 1993). Prototypes establish a common ground, allow designers and stakeholders to engage with a shared object, and facilitate the expression of thoughts and ideas (Jensen et al., 2017; Kelley & Littman, 2006; Scott, 2008).

Since the level of refinement and information contained in a prototype typically increase during the project (Ulrich & Eppinger, 2015; Yang & Epstein, 2005), stakeholders are often presented with less refined representations early, and recent studies have shown that this can influence how stakeholders perceive new ideas (Crilly, Moultrie, & Clarkson, 2004; Hare, Gill, Loudon, & Lewis, 2013; Lim, Youn-kyung et al., 2006). Several studies have shown that prototypes that are perceived as more attractive resulted in higher ratings of usability (Sauer & Sonderegger, 2009; N Tractinsky, Katz, & Ikar, 2000), and that prototypes with higher levels of refinement led to higher ratings of creativity (Kudrowitz, Te, & Wallace, 2012).

However, studies in the field of human-computer interaction have found that an increase in quality and functionality does not necessarily lead to better stakeholder input and recommend a balanced approach that might include the essential functionality but no unnecessary features (Hare et al., 2013; Lim, Youn-kyung et al., 2006). In addition to prototype fidelity, stakeholder background might also play a role when evaluating prototypes. Not all stakeholders share the same values and experiences. For example, a person with a technical background might be concerned with functional details, while another stakeholder might be more concerned about the social or environmental impact of a new concept.

Less refined prototypes require more cognitive capabilities that not all stakeholders might possess, which is particularly critical when stakeholders have limited domain knowledge. Parsons (1989) described a five-stage model of information processing, explaining that naïve participants tend to stereotype instead of moving through all cognitive stages of the model. Leder et al. (2004) described how a naïve reviewer of a painting might be satisfied with the simple recognition of or association with a familiar object rather than evaluating specific content and qualities that expert reviewers might observe. Recognizing that novices in any field tend toward emotional reactions rather than analytical evaluations (Winston & Cupchik, 1992) is critical because less refined prototypes have the potential to trigger emotional responses (Frijda, 1989; Scherer, 2003) that can result in misleading feedback.

Expertise and domain knowledge of stakeholders as well as prototype type and level of refinement can influence stakeholders' impression of an idea and the feedback they provide. Therefore, it is critical that designers do not leave these interactions to chance and instead create prototypes intentionally for use throughout the process, including and especially for, interactions with stakeholders.

1.1.5 Prototypes and aesthetic preferences in low- and middle income countries (LMICs)

The background and experience of stakeholders can influence the feedback they provide when responding to a prototype, and this may be especially important for designers to consider with regard to cultural context. For example, when looking at how consumers make purchasing decisions, Seva and Helander (2009) found that study participants from Singapore emphasized product functionality, while participants from the Philippines emphasized aesthetics. Similarly, a Human-Computer-Interface study with participants from Israel and Japan found that the correlations between aesthetics and usability varied between the stakeholder groups (Noam Tractinsky, 1997). These study findings suggest that stakeholders' perceptions and responses to prototypes might be influenced by the prototype itself as well as cultural and other individual differences.

1.2 Objective and motivation

Expert designers generally agree on the benefits of using prototypes throughout a design process, yet several studies have shown that novice designers tend to underutilize prototypes, specifically early in their design processes to gather input from stakeholders. Research on the utilization of prototypes has focused on how novices use prototypes for specific tasks like idea generation (Yang, 2009) but is limited as far as how novices use prototypes during other phases of design (Zemke, 2012). Further, it is unclear what distinguishes novice designers' prototyping behaviors and strategies from expert designers during a full design process (Björklund, 2013), including stakeholder engagement. Understanding these distinctions is a critical step in developing strategies to help novices leverage prototypes in their transition to design expert.

Based on expert designers' and scholars' recognition of the importance of prototypes in design, there is a growing body of research investigating how to teach novices how to use prototypes during design (Aranda-Jan, Jagtap, & Moultrie, 2016; Lauff, Kotys-Schwartz, & Rentschler, 2017; Menold, Jablokow, & Simpson, 2017). However, the already-crowded curricula (Dutson, Todd, Magleby, & Sorensen, 1997; Sheppard, 2001) in project-based engineering design courses might make it challenging to advocate for an increased use of prototypes even though this might support efficiency and project outcome.

In addition, while design experts and scholars alike advocate for the use of prototypes early in the design process to help frame the problem and to gather insight into stakeholders' needs and wants, little is known about how prototypes affect interactions with stakeholders, and what type of prototype, format or level of refinement is best suited to elicit stakeholder feedback. Current prototyping literature indicates that the type and fidelity of a prototype might influence the perception of an idea, but research in this area has focused on the use of sketches and virtual models (Kudrowitz et al., 2012; Macomber & Yang, 2011), and little to no research has looked specifically at how a variety of prototypes influences the feedback stakeholders provide.

Research is needed to understand when and how novice designers currently use prototypes and what prototype format is best suited to elicit stakeholder feedback to help inform recommendations and changes to how we teach design. The research presented here investigates the following research questions:

- How do novice designers currently think about and use prototypes during design in different contexts?
- How do novice designers' prototyping behaviors compare to prototyping best practices?
- How does prototype type, stakeholder group and question type influence stakeholder feedback?

More specifically, we investigated how novice designers in different contexts, particularly students who have completed a project-based, senior-level engineering design course in the United States and Ghana, used prototypes during semester-long projects, and how their prototyping activities compared to prototyping best practices. We also investigated how stakeholders responded to a variety of prototypes -- both low- and high-fidelity, as well as virtual and tangible prototypes, including sketches, mock-ups, CAD and 3D-printed models of a medical device.

Based on literature reviews and prior experience in engineering design, we expected that novice designers' conceptions as well as their actual use of prototypes would be underdeveloped. We expected to find that some common prototyping behaviors like "quick and simple" might be underutilized, and that novice designers would not yet have developed an understanding for the benefits that intentional use of prototypes can afford. Additionally, we expected that not all prototypes elicit the same feedback from stakeholders. We hypothesized that prototype type, as well as stakeholder group and question type would influence stakeholder feedback.

Some of this research includes projects from resource-limited settings. Adding cultural diversity that included participants (both designers and stakeholders) from different professional, cultural and geographical backgrounds reflects the challenges designers face when working on projects outside of their immediate surroundings and areas of expertise. Communication with stakeholders can be even more challenging when working across cultures, and the context-specific results of our studies have the potential to broaden the application of the findings.

1.3 Chapter overview

This section provides an overview and brief description of the individual chapters in this dissertation, including their motivation.

Chapter 2 describes a study designed to investigate how novice to informed designers in the United States conceived of and used prototypes during design. The study found that novice designers used prototypes frequently and for a variety of applications, but when evaluated through a lens of expert best practices, showed that their prototyping activities lacked intentionality and structure.

Chapter 3 describes a study designed to investigate how novice to informed designers in Ghana used prototypes during design. Similar to the findings in Chapter 2, this study found that novice designers underutilized prototypes and that their prototyping behaviors lacked intentionality and structure when compared to prototyping best practices. The study also showed that participants focused on virtual prototypes and seldom engaged stakeholders in the design process.

Chapter 4 discusses a study evaluating how the type of prototype, stakeholder group and question type influenced the feedback that stakeholders provided. The study found that tangible and higher-fidelity prototypes resulted in higher-rated feedback. The study also demonstrated that different stakeholder groups provided different feedback, and that question type influenced the feedback stakeholders provided.

Chapter 5 provides a summary of the individual studies as well as a summary of the dissertation. We continue to discuss the contributions and implications of this work and describe the limitations as well as recommendations for future work.

1.4 Research methods

In order to investigate the research questions above, we used qualitative research methods for data collection for all of our studies to elicit information from participants. Qualitative research methods allow for an in-depth exploration of topics, specifically when stakeholders are involved, and have already been used in a number of design research studies (Adams, Daly, Mann, & Dall'Alba, 2011; Ahmed et al., 2003; Ball & Ormerod, 2000; Bucciarelli, 1988; Cross, 2004; Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, McGowan, & Papalambros, 2013; Daly & Yilmaz, 2015; Mohedas, Kaufmann, Daly, & Sienko, 2015; Yilmaz & Seifert, 2011). We chose a semi-structured interview format as our method of inquiry for several reasons. With this interview format, questions are open-ended and designed to promote discussion, which is especially useful when conducting exploratory studies during which an understanding of a particular topic is sought. Weiss (1995) recommends semi-structured interviews as the most effective way to conduct interviews since they help create cooperation through an open and trusting alliance between the interviewer and respondent.

This interview format provides a structure to guide participants through the interview protocol (Boyatzis, 1998; Creswell, 2013; Patton, 2014), and enables the interviewer to address predetermined, critical questions in a conversation like manner. At the same time, the format allows participants to express their unique experiences and thoughts, and the interviewer to ask follow-up questions when clarification or additional information are needed. For example, if a participant mentions something interesting or unexpected, the interviewer has the freedom to explore a new angle that was not part of the original questionnaire.

While surveys have the potential to elicit input from a broader audience because they can be more easily distributed and require less time to administer and analyze, they do not provide interviewers with the freedom needed for follow up or clarification questions. We deemed this necessary because we wanted to learn from the unique opinions and experiences of the participants in our studies. The results from semi-structured interviews can be used to develop and inform survey questions that are well suited for data collection once the focus has been narrowed and the need for follow-up questioning has been diminished.

We chose not to conduct experiments to collect data for our studies because we were interested in how participants used prototypes throughout their entire semester long projects. Experiments are powerful tools for interventions and allow for direct observations that enable researchers to check and verify results. However, they are conducted over a limited time period, and the controlled environment does not always represent real-life situations, thereby potentially influencing the results yielded. The behaviors and responses of participants may not represent their actual behaviors since the circumstances of the experiment may not fully represent a natural context. While experimental settings are well suited to verify causation, they often do not allow insights into why participants performed a certain way (Creswell, 2013).

1.5 Expected contributions

The expected contributions of this work to engineering design, design education, industrial design, design science, and design research methods, as well as practitioners in professional practices, are as follows:

1. Deepen the understanding for how novice designers use prototypes throughout the design process, including with stakeholders.
2. Develop a framework of expert best practices for using prototypes during design.
3. Provide insight into how novice designers' prototyping behaviors compare to expert best practices.
4. Determine how prototype type, stakeholder group and question type influence stakeholder feedback.

The results identify deficiencies in novices' prototyping behaviors throughout the design process, including how they use prototypes to engage with stakeholders. Understanding how students' prototyping behaviors compare to prototyping best practices can be used to inform pedagogical methods to teach design. Based on these findings, strategies can be developed that leverage the use of prototypes as instructional tools and help novices to develop expertise in design.

Additionally, the results provide a framework of best practices for using prototypes that can be adopted by educators and practitioners. Educators can use the framework to help students develop prototyping strategies and to evaluate their prototyping behaviors. Practitioners can use the framework to inform their own strategies for using prototypes during design.

This research also illuminates how the nature and fidelity of prototypes influence stakeholders' perceptions of design concepts and the feedback they provide to designers. Both educators and practitioners can use these findings to develop prototyping strategies that are tailored towards a specific stakeholder group and help designers select questions that empower participants to respond, thereby improving stakeholder input and, in turn, design outcomes of a given project.

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Chapter 2 Novice designers' use of prototypes in engineering design

2.1 Abstract

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.

2.2 Introduction

Prototyping is a combination of methods that allows physical or visual form to be given to an idea (Kelley & Littman, 2006; Schrage, 1999) 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 are essential tools in the product design process and 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 (Kelley & Littman, 2006; Kordon & Luqi, 2002) to help designers identify design issues and learn from failures, which are essential functions to successful design. Therefore, many advocates suggest that prototypes should be created early and used iteratively throughout the product design process (Clark & Fujimoto, 1991; Yock et al., 2015). Tom Kelley, chief executive officer of the global design firm IDEO, calls prototyping "the shorthand of innovation" and encourages rapid and frequent prototyping (Kelley, 2007). Schrage argues that prototypes should be regarded as disposable artifacts to discover opportunities and quickly eliminate less promising solutions (Schrage, 1999). 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 make use of prototypes iteratively during this process of concept development, and use multiple and varied prototypes during all phases of product design (Crismond & Adams, 2012; Hilton, Linsey, & Goodman, 2015) to simplify complexity and achieve "small wins" at the component level (Gerber, 2009; Hilton et al., 2015). Working with prototypes at the component level and the ability to switch between component- and system-level thinking is an essential aspect of successful design practiced by experts (Gerber, 2009; 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; B. Camburn et al., 2015; B. A. Camburn et al., 2013; 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 expert designers 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, 1999; 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; Mohedas, Daly, & Sienko, 2015; Mohedas, 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). Prototypes provide a fundamentally different way of communicating around, in Schrage's terms, 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 the 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 the design process is essential 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., V. 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, meaning novices' use of prototypes have not been captured in an authentic setting throughout an 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 entire engineering design processes. Since experimental settings without any long-term implications and personal investment such as grades might influence how participants act, we looked at participants' prototyping behaviors in context. We investigated how novice designers reported using prototypes during a real design project, and compared their reported prototyping activities to prototyping best practice behaviors.

2.3 Research design

This study was designed to answer the following research questions:

1. How do novice designers conceptualize prototypes?
2. How do novice designers use prototypes in practice, including to engage with stakeholders?
3. 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 they have been used in numerous design practice studies (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.

2.3.1 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 research methods, such as interviewing, that facilitate in-depth explorations of participants' experiences.

The majority of the 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 required the consideration of the whole design process (here, 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 spanning definition to evaluation. A detailed distribution of participants based on gender, design course, and prior design experience is shown in Table 1.

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**

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.

2.3.2 Interview protocol development

Data were collected through semi-structured interviews with the participants. Interview questions were designed to investigate and collect detailed descriptions of 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 the 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.

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 type of information did you think critical 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?

2.3.3 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 one 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 and allowed 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?"
- "What role did prototypes play during stakeholder Interactions?"

2.3.4 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 novice designers reported using prototypes
- How novice 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, 1999; Yock et al., 2015). While some research on prototyping practices in product design exists (M. B. A. Camburn, Dunlap, Viswanathan, Linsey, & Jensen, 2013; Christie et al., 2012; V. K. C. 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 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, fidelity, structure, 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 prototyping best practice are included in Table 9 in the Appendix:

(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.

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
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

2.4 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.

2.4.1 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 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	3	[A prototype] could be...just a sub-assembly that's put together to show how a particular

	design that doesn't have to represent the whole assembly.		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.

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?"

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).

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).

2.4.2 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.

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...
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 a metric, 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.

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. In “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 to 15 designs on paper just to look at what ideas we can use and how this would meet our engineering specs" (Participant 16).

In “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 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).

2.4.3 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 lowest number of 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.

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 (or 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.
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 to help select concepts.	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.
Delegate	Prototypes are used to split individual responsibilities and tasks in the project.	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 (ergonomics or human factors) such as the evaluation of size, comfort, weight, appeal of a layout, etc.	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.

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 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).

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).

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

Since stakeholders are critical throughout the design process, the study team included a specific focus on how novices reported using prototypes to engage with them. 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.

Table 8 Codes describing 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	13	When we showed our physical models to doctors, they gave us feedback, and we were able to use the feedback to make changes.

	design decisions.		
Define problem	Used prototypes with stakeholder 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 (ergonomics or human factors) such as the evaluation of size, comfort, weight, appeal of a layout, etc.	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.
Select concept	Used prototypes to have stakeholders help pick the final concept or provide information 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.

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 most frequent prototype use with stakeholders was “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 collect and incorporate 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).

2.4.5 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?

To find out, we used a deductive coding approach to compare participants’ statements to prototyping best practices. 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.

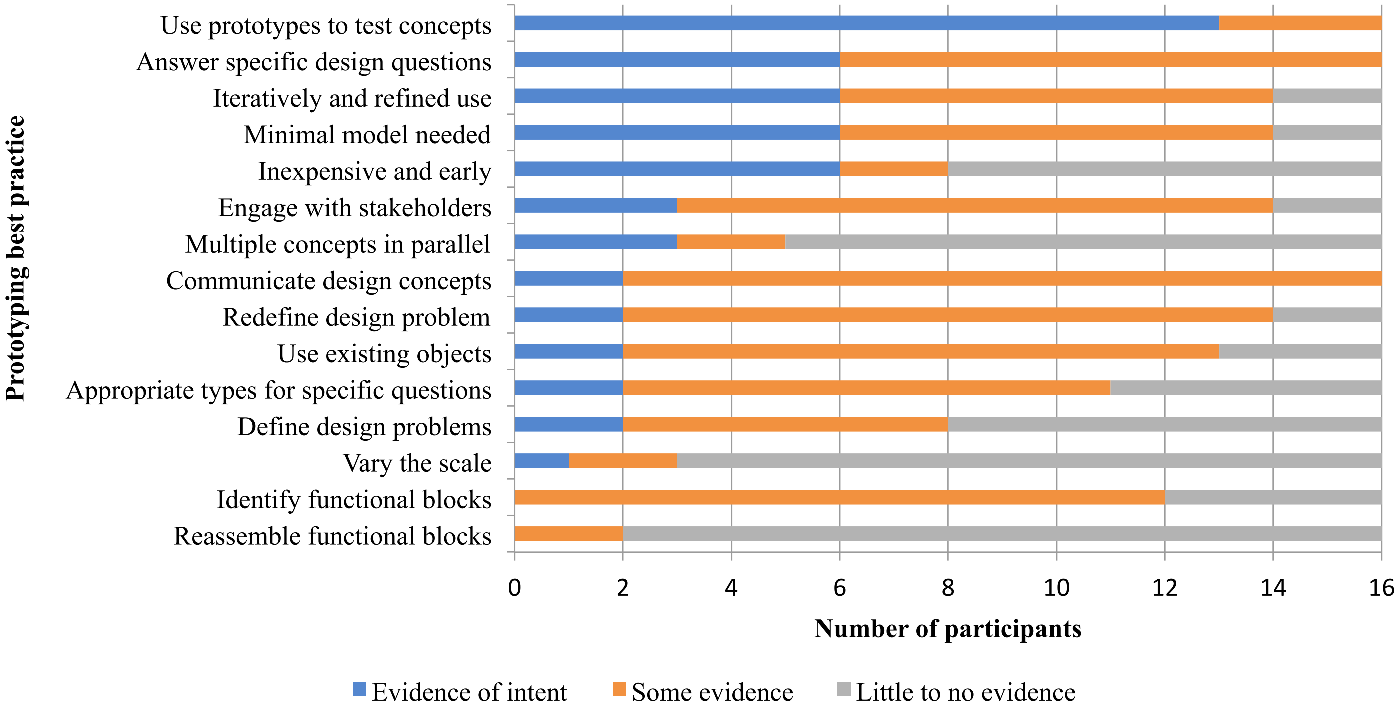

Figure 1 To what extent did novice designers engage in prototyping best practice?

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 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 mock-ups 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 the visually impaired 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 the stakeholders 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 this. While 12 participants engaged in the related “Identify and prioritize functional blocks” behavior earlier, only two of the participants were able to and/or attempted to reassemble all of the refined functional blocks back into a complete concept model, and only three participants mentioned earlier 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 the functional blocks identified earlier 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 were 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 multiple prototypes at the same time to observe their stakeholders, 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 can 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].”

2.5 Discussion

2.5.1 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; B. Camburn et al., 2015; B. A. Camburn et al., 2013; Christie et al., 2012; 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 on participants' part; 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).

2.5.2 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 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.

2.5.3 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 as well as the potentially limited retention of the benefits they did experience (Christie et al., 2012; Crismond & Adams, 2012; Hilton et al., 2015; Kelley, 2007; Kelley & Littman, 2006; Schrage, 1999; Viswanathan, Atilola, Goodman, et al., 2014; Webber et al., 2016).

For example, novice designers reported only limited use of prototypes during the early stages when user requirements and engineering specifications were being defined. Here, best practice calls for the use prototypes to elicit input and feedback from stakeholders to define a design problem (Kelley, 2007; Yock et al., 2015). And while six of the participants in this study reported using prototypes to refine design problems in accordance with prototyping best practice, only two of the participants reported using prototypes early in their projects to define the design problem. Instead, novice designers reported primarily using prototypes to engage with stakeholders later in the design process to share their progress and gather feedback (Mohedas et al., 2014a, 2014c).

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, 1999).

2.6 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 look 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.

2.7 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. In the future, 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 stakeholder'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 learning 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 (B. Camburn et al., 2015; B. A. Camburn 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.

2.8 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.

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2.11 Appendix

Table 9 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**
Use prototypes to test concepts	Prototypes are used to test a concept or idea	Little or no evidence of behavior	Used prototypes to test parts or elements of the concept	Used prototypes to test individual parts or elements as well as the whole design concept
Use prototypes to answer specific design questions	A specific question is identified and prototypes are created to find the answer	No particular questions, built prototypes for other reasons (i.e. required deliverable)	Questions arose from building prototype; expected questions, but did not know the specifics, created	Intentionally asking specific questions and creating prototypes to find solution (i.e. size)

			prototypes without knowing what to ask	
Use prototyping iteratively and develop increasingly refined prototypes	Prototypes get more and more refined and incorporate additional knowledge	Little or no evidence of behavior	Evidence of incremental changes and improvements	Strong evidence of refinement, including changes to project objective
Design the minimal model needed	Only what is needed to answer the question is prototyped, leaving off unnecessary features	Created the full model, did not focus on what is needed	Created more than what is needed to answer the questions	Prototyped only what is needed to answer the question, left off unnecessary
Use prototypes to communicate design concepts	Prototypes are used to communicate ideas to team members and stakeholders	Little or no evidence of behavior	Unintentional or accidental use of prototypes for communication (showing because it was on hand), not inclusive across stakeholders or team members	Intentional use of prototypes for communication, both to teammates and stakeholders
Use prototypes to engage with stakeholders	Prototypes are used to engage with stakeholders	Little or no engagement with stakeholders	Used prototypes to engage with stakeholders to show progress and receive general feedback	Used prototypes to engage with stakeholders to intentionally ask specific questions and allow feedback to define/refine user requirements
Use prototypes to refine design problem definitions	Later use of prototypes leads to refining of design requirements and specifications	No prototype use or not implementing any changes to problems and solutions based on feedback received	Unintentional or non-specific use of prototypes leads to changes to problems and solutions based on feedback received	Intentional use of prototypes to gather feedback on specific problem and solution details
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	Unintentional reference of existing product (as heavy as this object?)	Unintentional, on-the-spot creative use of existing products to create new feedback (would a handle like this work on the new design?)	Used or incorporated existing products or parts into prototype, purchased or harvested mechanism and used in prototype. Modified existing products into new prototype for feedback

Use inexpensive prototypes early and efficiently	Simple and inexpensive concept models are built to learn additional information (trial and error prototyping)	Little or no evidence of behavior	Some evidence of behavior	Intentionally constructed simple and cheap models of multiple concepts
Use appropriate types of prototypes to address specific design questions	Select the best-suited prototype format to address a specific questions	Only built one prototype format	Used multiple prototype formats but did not say why format was chosen or chose because format was readily available	Selected the most appropriate format best suited to address specific questions and explicitly stating the reason for choosing format
Identify, prioritize and isolate functional blocks of prototypes	Features (functional, aesthetic, etc.) that need to be prototyped are determined	Little or no evidence of behavior	Identified single functional blocks or missed blocks	Identified multiple functional blocks with the intention to learn from block and influence project
Use prototypes to define design problems	Early use of prototypes leads to defining of design requirements and specifications	No prototype use or not implementing any changes to requirements / specification based on feedback received	Unintentional or non-specific use of prototypes leads to changes to requirements / specifications based on feedback received or used later during project (refining rather than defining)	Intentional use of prototypes to gather feedback on specific details, used early during project to define
Develop prototypes of multiple concepts in parallel	Multiple concepts are prototyped in parallel to select the most promising approach	Created only one prototype at a time	Created multiple prototypes but not to aid with selection, or not in parallel	Created multiple prototypes to select from multiple ideas
Vary the scale of prototypes	The scale of a prototype is adjusted when appropriate to make construction easier	Did not vary the scale	Varied the scale of an individual feature or element	Repeated scaling of individual features and elements or scaling of the full prototype
Reassemble blocks into complete concept models	Re-integrate what has been learned from the functional blocks into the whole concept model	No reassembling of functional blocks	Identified functional blocks but did not work on all of them, or did not use what was learned from functional blocks to influence design	Identified and worked on multiple functional blocks, learned from blocks and used knowledge to influence design

Chapter 3 Investigating Ghanaian novice designers' use of prototypes during design

3.1 Abstract

Prototypes are fundamental tools in the product design process and experienced designers regularly use them iteratively, and during several phases throughout the design process, to identify, select and refine the most promising concepts. Prototypes allow for easy sharing of ideas between design team members and stakeholders, as well as for the evaluation of human factors. However, in engineering education, prototypes are often built only to test and evaluate a chosen design, and iteration occurs not intentionally, but when a model is not performing as expected, depriving designers of the benefits that frequent, quick and simple uses of prototypes can afford. Increasingly, products are designed for global markets, yet studies on design practice primarily investigate designers who design in, and for, high-income countries. To better understand how designers in low and middle-income countries (LMIC) approach design, we conducted interviews with novice designers from one LMIC setting, here Ghana, a middle-income country (MIC). We examined how Ghanaian students used prototypes throughout their semester-long design courses, compared their reported use of prototypes to prototyping best practice behaviors, and analyzed the types of prototypes they used. We found evidence for the use of some critical prototyping best practice behaviors, while other behaviors were underutilized. We also found that virtual models dominated the prototyping choices of Ghanaian novice designers.

3.2 Introduction

Professional designers have long recognized prototyping as an effective technique for product development and consider prototypes an essential tool in the product development process (De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Viswanathan, Atilola, Goodman, & Linsey, 2014; Yang & Epstein, 2005). Due to practical reasons like timing and funding constraints, prototyping is often listed as a phase and occurs only as an activity to test and evaluate a chosen design in engineering design education (Dieter & Schmidt, 2012; Dym, Little, Orwin, & Spjut, 2009; Tayal, 2013). But experienced designers, and designers in other disciplines (e.g. industrial design), frequently use prototypes iteratively throughout the design process to quickly learn from, and select the most promising concepts (Kelley, 2007; Schrage, 1999). This iterative use of prototypes enables designers to move from preliminary to more refined prototypes and incorporate knowledge gained from previous generations.

Based on professional designers' and scholars' recognition of the importance of prototypes in design, a growing body of research investigates the use prototypes during design (Aranda-Jan, Jagtap, & Moultrie, 2016; Lauff, Kotys-Schwartz, & Rentschler, 2017; Menold, Jablokow, & Simpson, 2017). Several studies have found that novice designers tend to spend less time on individual design tasks and use prototypes during fewer stages of the design process, limiting the benefits that the iterative use of prototypes can provide (Atman et al., 2007; #1 Authors, 2017; Häggman, Tsai, Elsen, Honda, & Yang, 2015; Viswanathan, Atilola, Goodman, & Linsey, 2014; Yang & Epstein, 2005).

Prototypes can also serve as devices of communication within the design team as well as with stakeholders. Here, prototypes can provide a fundamentally different way of collaborating by creating a "shared space" for the participants (Schrage, 1999). Well planned communication is particularly crucial during the early stages of a design project when designers strive to develop a thorough understanding for their stakeholders' and end users' needs and wants (Mohedas, Daly, & Sienko, 2014). Experienced designers often use prototypes to observe stakeholders' interactions with models and use this information to develop requirements and specifications when the project scope is defined, and later redefined (Kelley, 2010). Involving stakeholders during the design process can help with the successful adoption of a new product and is widely used among expert designers.

Many researchers have shown that prototyping with a purpose, or having a strategy for using prototypes is critical for a successful design outcome (Christie et al., 2012). Factors like number of prototypes, types of prototypes and time of use, among others, influence how a project progresses, and an effective and intentional use of prototypes can have tremendous impact on project outcomes. And even though an increased use of prototypes might support efficiency, it might be challenging to advocate for this in the already-crowded engineering design courses curricula (Dutson, Todd, Magleby, & Sorensen, 1997; Sheppard, 2001).

In a previous study with novice designers from a university in the United States, the authors recorded limited access as one of the frequently reported reasons for why participants did not engage with stakeholders (#1 Authors, 2017). This was particularly noticeable when participants worked on projects intended for use in LMICs, an area of increased interest to the design community. In this study, we investigated how novice designers from a university in Ghana used prototypes when designing products intended for their local communities. We discuss how local constraints impact their design practice, compare their reported behaviors to prototyping best practices and explore possible implications for engineering design education.

3.3 Research methods

With this study, we sought to answer the following research questions:

1. To what extent did Ghanaian novice designers follow prototyping best practices?
2. What types of prototypes did Ghanaian novice designers use during their project based design courses?

We used a qualitative research approach for this study to develop an understanding for participants' experiences (Boyatzis, 1998; Creswell, 2013; Patton, 2014), and capture how they reported using prototypes during their project based design courses. This was done through semi-structured interviews that allowed participants to freely express their individual experiences and thoughts, while still providing some guidance as they reflected on their design projects (Ball & Ormerod, 2000; Bucciarelli, 1988; Daly, McGowan, & Papalambros, 2013; Mohedas, Sarvestani, Daly, & Sienko, 2015; Yilmaz & Seifert, 2011).

3.3.1 Participants

We enrolled 33 students from a university in Ghana in this study to investigate how novice designers used prototypes during their project based engineering design courses. The study population represented a group size sufficient to conduct detailed explorations of participants' experiences and identify transferrable trends of the findings (Björklund, 2013; Cash, Elias, Dekoninck, & Culley, 2012; Crilly, 2015; Stempfle & Badke-Schaub, 2002). All participants had completed either a third or fourth year undergraduate, project-based engineering design course, and some students had participated in extra-curricular, academic design activities, had experience as a teaching assistant, or had completed an internship. Participants in these design courses followed a common engineering design process (Dieter & Schmidt, 2012), worked in teams, and completed deliverables such as project presentations and design reviews. All teams had to prepare a final presentation and project report by the end of the course.

Even though some participants reported prior design experience, we considered them novice designers due to their limited exposure and experience with team based design projects that required them to apply their skills to a project challenge that encompassed the entire design process. We did however expect a range of design and prototyping skills based on participants' previous experiences. The demographics of the study population are shown in Table 10.

Table 10 Participant demographics

Gender		*Capstone Design Course*			*Extracurricular Academic Design Experience*		*Internship/ Work Experience*	
Male	Female	BME 300	BME 400	Food Processing 400	Yes	No	Yes	No
28	5	21	11	1	8	25	4	29

3.3.2 Interview protocol

The research team used an existing interview protocol developed for an earlier study with novice engineering designers from a Midwestern university in the USA (Authors, 2017). This semi-structured interview protocol was designed to capture how participants conceptualized and used prototypes during their most recent design courses, and approved by the Midwestern University's IRB. The questions focused on the roles of prototypes during the individual design phases, and encouraged participants to express their experiences while allowing the interviewer to ask follow up questions. The main themes and sample questions of this interview protocol are shown in Table 11.

Table 11 Interview protocol main themes and sample 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 type of information did you think critical 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?

3.3.3 Data collection

The participants for this study were recruited by a teaching assistant in the engineering department of a university in Ghana. The teaching assistant reached out to recent graduates of 300/400 level engineering courses via phone and email, and scheduled interview times following the semester's conclusion. Participants were presented with an informed consent form, agreed to be audio recorded for later transcription and analysis, and received a small amount of money for their contribution. Personal data collected throughout the study was de-identified for data storage and analysis. One person conducted all interviews and at the beginning provided the following, broad definition of prototypes to participants: "Prototypes are three-dimensional physical models, CAD models, or two-dimensional sketches or representations that communicate an idea or a design concept" to ensure that all participants based their answers on the same definition when reflecting on how they used prototypes during their design projects. The participants were then encouraged to describe their projects in chronological order and elaborate on their prototyping activities as they occurred during the individual phases they completed. Examples of the interview questions included:

- "What prototypes did you use to understand the problem?"
- "How did you use prototypes to develop user requirements?"
- "What role did prototypes play during stakeholder interactions?"

3.3.4 Data analysis

The research team then used a deductive analysis (Crabtree & Miller, 1992) to determine how the reported prototyping behaviors aligned with prototyping best practices. An existing codebook that was developed during a previous study was used to analyze the data (#1 Authors, 2017). These codes focused on expert prototyping best practice behaviors and recommendations and were derived from prominent engineering design textbooks (Cross, 2007; Dieter & Schmidt, 2012; Ertas & Jones, 1996; Kelley & Littman, 2006; Otto & Wood, 2000; Schrage, 1999; Yock et al., 2015). In addition to some research that exists on prototyping best practices (Camburn et al., 2013; Christie et al., 2012; Viswanathan, 2012; #2 Authors, 2017), these textbooks are frequently referenced in engineering design courses, and while potentially incomplete, allowed for a comprehensive collection of prototyping best practices.

QSR's NVivo 11, qualitative coding software, was used by two team members to analyze the transcribed interviews and determine if, and to what extent, the participants reported following prototyping best practices. Each participant's reported prototyping behavior was rated on a three-point scale (0-1-2) that considered intentionality, fidelity, structure, and iteration of the activity, and discounted referencing existing objects for benchmarking. The criteria used for this rating are shown in Table 12, and a full list of the prototyping best practices including detailed rating criteria and coding results can be found in Tables 14 and 15 in the Appendix.

Table 12 Criteria for rating prototyping best practice behaviors

Rating	*Definition*
(0)	Indicated little or no evidence of the behavior
(1)	Indicated some evidence of an intermediate behavior
(2)	Indicated alignment with best practice

The coded sections identifying prototyping activities were then examined to determine what type of prototypes participants used during their reported prototyping activities. The codes for this analysis distinguished between virtual and physical prototypes and a detailed description can be found in Table 13.

Table 13 Definitions for virtual and tangible prototypes

Prototype type	*Definition*
Virtual	No tangible objects, but sketches or CAD models
Physical	Existing or fabricated, tangible, physical objects.

3.4 Findings

3.4.1 To what extent did Ghanaian novice designers' reported behaviors follow prototyping best practices?

We first examined how participants followed prototyping best practices during their design courses. Figure 2 depicts the findings of this analysis and shows how many participants reported engaging in the individual prototyping best practice behaviors with either an indication of alignment with best practice, some evidence of an intermediate behavior, or little to no evidence of the behavior.

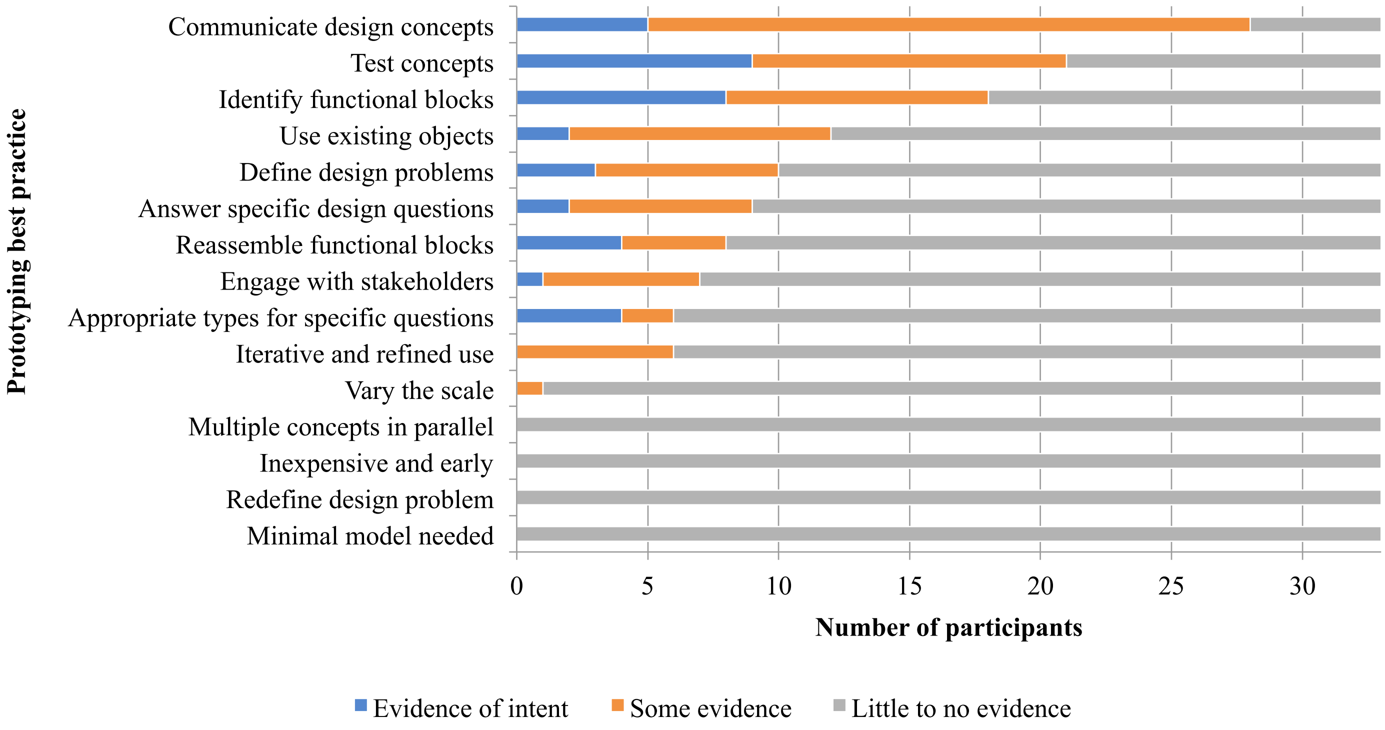

Figure 2 Coding results for the reported use of prototyping best practices by Ghanaian novice designers

Communication was the most frequently reported prototyping behavior. 5 participants reported activities that aligned with this prototyping best practice, and 23 showed some evidence of an intermediate behavior. Participant 31 provided a summary of what the majority of the participants experienced:

Sometimes I am working on a project and… those around me don't understand it as I understand it. I can talk to you for hours about this, but a picture conveys a better idea than me talking about it. So that's the main essence for better communication to my audience.

Participant 1 echoed this insight with a similar statement: “Sometimes you have in mind what you are doing, you would say this is what you want to represent. But when you don’t show it to someone else, [they] will be thinking of something else.”

Communication occurred between a variety of people, and Participant 19 found that prototypes helped to make sure that communication within the team members was effective an that people had a good understanding of what others are thinking: “Sketches were used to communicate, as in we were a group and we were discussing, looking at possible solutions. So if somebody brings an idea, if we don’t sketch it down, other people might not understand what the person is trying to imply so that why we were putting the sketches down. So somebody will come out with a sketch and we’ll be like no this part needs to change that part, so we will have an idea where we are moving on to and what we are really talking about, so that’s how come we used sketches throughout.”

This was echoed by Participant 25: “Sketches just made people, or made our colleagues understand what we really wanted to come up with.”

In more detail, Participant 3 described how prototypes were essential as communication tools for the completion of their project: “I think it would have been very impossible to have our project complete our project without prototype, because at various stages of the design process, we had to communicate with each other… With sketches and 3D models, we were able to get the idea of members of the team and we were able to build on that to get the better design. In fact it improved the communication with our team.”

Participant 4 explained how prototypes were essential for sharing information outside of their team, here classmates and instructors: “Without [prototypes], we don’t think we will be able to show to the class, to prove to our supervisors that we've done a great job. We were able to prove ourselves and show that we've done something."

Only five participants reported little to no evidence for using prototypes to communicate. A lack of time was frequently mentioned and Participant 31 explained how the project timeline did not allow the team to involve their stakeholders to collect feedback on their concept: "Circle that back to the stakeholders…? No I wished I could have done that, but considering the duration… it will be difficult to go back and see what they want. That would have been the best to do."

Other participants involved stakeholders but deliberately shared prototypes only selectively. Participant 29 described that the team did not expected all stakeholders to be prepared to provide input: "I didn't show to nurses - Ok I showed it to the technician alone, not the nurses, because they don't understand technical stuff like that, so it was my supervisors and the technicians who had [a] chance to look at that and then approve before I move on to the next stage."

Testing a concept was the second most frequently recorded prototyping best practice behavior. Nine participants reported behaviors that aligned with this prototyping best practice, and 12 showed some evidence of an intermediate behavior. Participant 1 described in general terms the importance of testing: "I have to evaluate my product to see if it suits my customer's requirement. So I have to make sure I validate that, whether what I'm doing, am I following in line with what I said from the beginning. Have I been able to achieved my specifications, have I met my target, and have I met my customer's needs?"

Participant 30 laid out an iterative approach to testing that allowed the team to move through several iterations of their project: "So based on the result of the simulations, I noticed it was going to work so I decided to put it in a mockup and come up with something to show physical something, not a computer… so I bought the aluminum and I got the final and I designed it."

Participant 12 provided more detail and explained how the team tested the insulating properties of their design for a device to transport blood. The team started with virtual models and moved to physical testing to verify their findings: "We did simulation with the MATLAB. We had data that we see [in] the graphs, the warming process, this is the heat going in and this is the temperature of the blood bag that was changing. We were taking the temperature of the blood bag at specific time period as well as the voltage that we were using. So we were able to obtain some data on it and we could see that ok, yeah this is the warming process over 10 minutes. So we see this kind of curve; it peaks and then it plateaus."

However, testing wasn't always a straightforward activity, and Participant 6 described a struggle based on compromised material selection: "I went on testing if that concept would actually work. I was able to get some readings but then because of the selection that I made for the electrodes… It was supposed to be nickel and copper... but… I had to settle on lead on lead and, so because of that, that actually gave me a very weak signal."

12 of the participants showed little to no evidence of this prototyping best practice behavior. Participant 25 explained what many teams found, that they did not have enough time to learn the necessary skills for testing: "Because we had to learn the software, procedure and other techniques and do it at the same time, it was a bit stressful. The time too was short so we couldn't really finish up the work."

Participant 11 also reported limitations to their testing activities that influenced their decision making process: "We actually were supposed to test… but unfortunately because we couldn’t do that, we just decided… we didn’t actually [have] empirical evidence to prove that here will be better than here or maybe here. I’m sure probably if we had been able to test, we would have made some adjustments.”

This was echoed by Participant 31 who expanded on how the team was not able to simulate flow with their CAD model, and used an alternative, mathematical method instead: “I wanted to use CDF AutoCAD to do the free flow and I don’t have the software, yea so basically I wish I could have got help from somebody. I interacted with so many people but I didn’t get anybody to help me. So I resorted to using excel solver to just run optimizations based on the equation I had.”

Participant 9 explained how their team also had to compromise based on time and skills, but was able to proceed with a software simulation. However, the team did not think this approach as successful as if they had constructed a functional prototype: “Because we didn’t really build a final working, let me say prototype, we used SolidWorks to simulate maybe the pumping and then the absorption of water by maybe a silica gel so we saw how the whole thing will be like and then the SolidWork[s] generated a word document that is kind of like a report of the testing. So we would have done some kind of like testing, real hands on testing if we had had the prototype, maybe the working prototype, but because we didn’t go that far because of the time for the semester and then other courses that we need to be taking we ended up, we had to opt for the software.”

Identify functional blocks was the third most frequently reported prototyping best practice behavior. Functional blocks are typically considered key components that are critical to the success of a device. Eight participants reported behaviors that aligned with this prototyping best practice, and 10 showed some evidence of an intermediate behavior. Participant 27 explained the main components of a device to prevent mosquito bites: “We had three main ways that the mosquitoes get attracted… The fan that sucks the mosquitoes into the device… And then for the extermination we considered electrocuting the mosquitoes after they’ve been attracted, or using a sticky trap to trap them.”

Participant 11 elaborated how asking specific questions helped the team with the design of a cooking stove: “What are some of the ways of maybe conducting the heat? Maybe the heat regulation, we decided to put a regulator there and a conducting system. Where our smoke is going to come out? So we decided to incorporate a chimney system into it. And that’s where we decided to place our filtering system.”

Likewise, Participant 2, who worked on a glucose-monitoring device, described in detail how breaking up the device helped the team address several questions: “So I had to look at the power of the pump, the weight of the pump because it’s going to wear it on the arm. I had to consider the electrodes, the size of the electrodes, what amount of current will pass through the electrodes. The weight, the mechanisms, how finely it can be tuned, the flow rate, how much power it needs. The insulin chamber, the injection, the size of the needle, because that really affects how much pain the patients goes through, and I’m trying to make it as less painful as possible.”

However, 15 participants did not consider functional blocks and instead worked on their project as a complete system. Participant 16 explained: “Ok we were analyzing the system as a whole we didn’t divide it into sections.”

Similarly, Participant 26 who worked on a portable massager didn’t build any physical prototypes or investigate individual components. Instead, the team but based assumptions on virtual sketches and estimations of the complete model:

"Let's say if I took the light weight, because the actual prototype wasn't built, but it was in sketches, so I didn't know the actual mass but I intuitively… I think it was less than 500 to 750 grams yeah…"

Another critical prototyping best practice that is closely related to communication is ***engage with Stakeholders.*** We only recorded one participant at an advance level, and six participants showed evidence of an intermediate behavior. Participant 31 who we recorded at an advanced level, explained how existing products were used to get feedback from stakeholders on the appropriate weight of a device component: "I communicated with them like 'what do you really define as not too big?' They picked an ultra sound Doppler, so they said this is ok, so I checked the weight of the ultra sound"

Participant 19 described how various prototypes not only helped the team with explaining the work they had completed, but also with gathering feedback from stakeholders: "When you communicate with people with just words, people have different conceptions about what you are trying to put across, but when you show them prototype, sketches or the CAD model, they can actually confide what they are thinking about to a specific design. So it helped us put across or all the work that we did from material selection, concept generation, idea generation into that model."

Similarly, Participant 24 described how stakeholders helped the team to better understand the problem, and also how they provided feedback on early suggestions: "They told me more about the problems… A few gave me ideas, but then I proposed ideas to them: 'do you think that if you had something that was much smaller, would it be fine?' And they will say: 'yeah, maybe this will be so good.' 'You think something that is much softer to clean the ear, would it be ok?'

They say yeah: ‘I think something which is soft is good for the ear, not something which is too hard.’”

Aside from these positive results, we recorded little to no evidence for 26 participants for using prototypes to engage with stakeholders. Many stated a lack of time and relied on personal experience and literature reviews instead of engaging stakeholders to collect input and requirements. Participant 10 explained: “It was from literature review and it was from personal experience that we got the ideas. We had confidence that we were correct because based on where we got the information [from] we had confidence that it was correct.” The same person added later: “It would have been helpful for us if we would have gotten more stakeholders to be involved into the work.”

Participant 14 also mentioned referencing literature and the team using themselves as stakeholders: “Like we could have involved them [stakeholders] in the selection of concept but because it was an academic work, we just decided to select the concept and give it our own and score it based on the literature.”

Participant 10 justified why the team didn’t engage more with stakeholders and referred to the course structure and a lack of time: “I think it all depends on our course that we did. If they could allow us have some let’s say time slot within the academic schedules where we can go out there to have contact with our stakeholders.”

Time was the most often reported limiting factor for engaging stakeholders as the following participants explain: “Basically, we didn’t go to the stakeholders as I said earlier but we took ourselves as stakeholders and looked at it at that way.” (Participant 21), and “So time didn’t permit us, that’s the main reason why we didn’t go to the hospitals and catch doctors and maybe get enough ideas to support the work.” (Participant 13)

Participant 12, who engaged with medical professionals, found that their stakeholders were too busy and as a result, the design team decided to make decisions on their behalf: “We didn’t really have that [conversations] because they’re always busy so we don’t have that direct contact with them. At some point we needed to make a decision on their behalf. We needed to adapt the Apple rule: design the thing that people don’t know [they need], but design things that they think people will like.”

The least frequently reported prototyping best practice behaviors where all participants exhibited little to no evidence included ***redefine design problems***, use ***inexpensive prototypes early and often***, and use ***multiple concepts in parallel***.

3.4.2 What types of prototypes did Ghanaian novice designers use during their project based design courses?

Next we examined what types of prototypes participants used during their reported prototyping activities. We distinguished between virtual and tangible prototypes and Figure 3 shows the distribution of the prototyping categories within the individual prototyping behaviors.

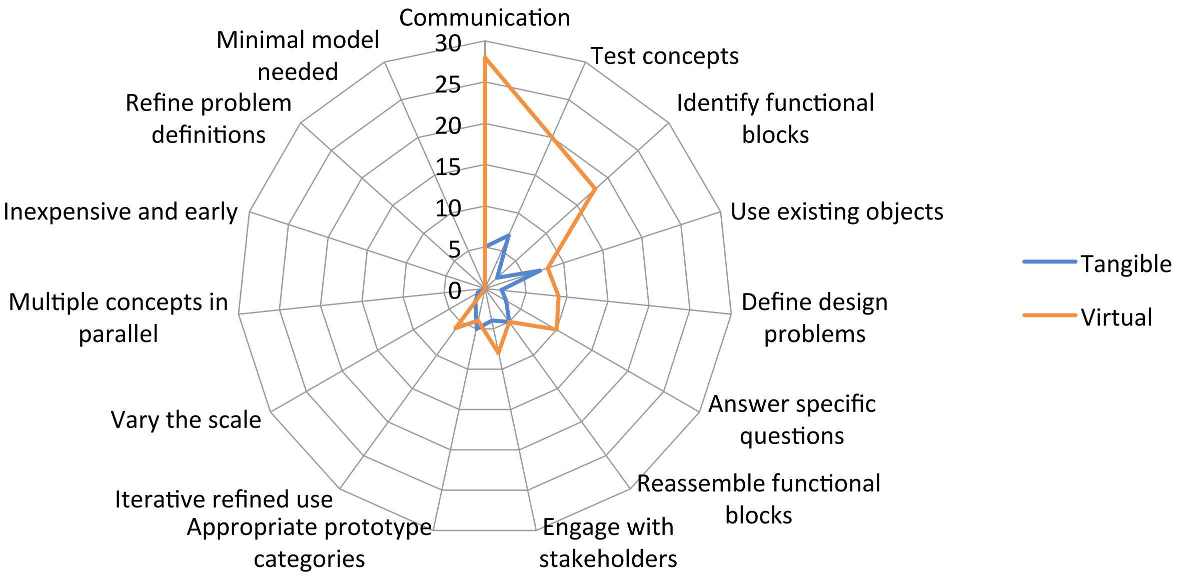

Figure 3 Coding results for use of virtual and tangible prototypes within the reported prototyping best practices by Ghanaian novice designers

Communication was not only the most frequently reported prototyping best practice behavior, but also the one for which we recorded the highest number of prototype uses. 28 participants reported the use of virtual prototypes for this behavior, and 5 participants used tangible prototypes to communicate. The participants who reported using tangible prototypes for this activity emphasized the benefits, and Participant 22 explained how their stakeholders moved from having questions to providing feedback on the proposed design once the team introduced physical models: “The impact as the building physical models, it really gave the lectures, our supervisors the idea of what we were really trying to do because when we started it, we had more questions coming to us, like how is it going look like, so the time we presented our model, we had less questions, it wasn’t even a question, it was a comment.”

The majority of participants described using virtual prototypes for communication. Participant 19 described how virtual prototypes helped communicate with people outside of their team: “When you communicate with people with just words, people have different conceptions about what you are trying to put across, but when you show them prototype, sketches or the CAD model, they can actually confide what they are thinking about to a specific design. So it helped us put across or all the work that we did from material selection, concept generation, idea generation into that model.”

Participant 11 noticed that once they used prototypes, people became more interested in their project because they added a sense of realism: “When we started using the CAD… you know some of those people, they started gaining interest that wow, so this is how the whole thing is like and they were very happy. So when we started using it and they started something they realized that oh after all, this thing is feasible. So is like before you use the CAD sometimes you find the thing so difficult to achieve or maybe you don’t see the feasibility of it but it was when we started using the CAD we started getting something.”

Participant 2 also found this to be true: “CAD was very helpful because it helped people see what you are trying to do. It helped people understand. The CAD model, it made it like, oh ok, this is it. Oh ok, it moves from here to here to here.” The same person later added that for this particular activity, virtual prototypes were easier to create than physical ones: “It made it very easy and helpful and it was easier to use than building the physical model component. It was far easier that building actually building it."

Participant19, who had already acknowledged the benefits of using prototypes, added distinctions between different levels of prototype refinement: "If it was just the sketches, it will not be as easy as it was with the video form from CAD design."

Participant 14 explained how the team used sketches to get feedback and input from stakeholders: "So we had to like draw this for them, with the dimensions, this fertile monitor… we showed them the dimension of this or that, which one will you prefer. They gave us like oh it should be shorter than this, this part should be shorter, this part should be taller, they gave us all the dimensions then we approximated them to get the length."

Testing was the second most frequently mentioned prototyping best practice behavior, and 20 participants reported the use of virtual, and seven the use of tangible prototypes. The participants who reported the use of physical prototypes to test their device often also reported the use of virtual prototypes. Frequently, the physical models were used to verify the virtual test results.

Participant 31 explained how the team moved from earlier, virtual testing to building a physical model to verify their results: "The goal for building a physical model was to validate the operation of the device. Just to see how in reality, whether they will perform in a similar manner as [the virtual] model."

Participant 12 also explained how the team performed physical tests in addition to, and to verify the virtual results: "We built physical model and we analyzed. Yeah we had a physical bag, but later on not with the blood; for the blood it was difficult to actually test with the blood so… we were using sachet water. Yeah so based on that we know that if we warm the water it might be close to warm blood; so it was just the simulation that was trying to test to see whether the warming process is [real].”

Several participants realized the benefits that tangible prototypes can afford, even if they were not able to use them. Participant 17 described how the team found physical models better suited for testing than virtual prototypes: “CAD or software or sketches, some might be, some could be used alright but I think the most efficient one to try and use will be the physical model.”

Similarly, Participant 14 started with a virtual simulation, and then built a physical prototype to test the concept: “So I first did the simulation [in] Proteus with the Arduino, then I came to the physical model… to prove my concept that what I have done is feasible. My physical [model] goes to verify [the concept].”

Participant 5 posited that a computer generated model might not always match the results of testing a physical model: “For the computer model, it can work on a computer simulation but when you bring it out of there to the physical model, it might fail you, it might not perform actually what you saw on the computer.”

This mistrust in the virtual environment was also voiced by Participant 9, who expressed concerns about the validity of the materials that were available in a simulated environment: “The material has certain properties that maybe were modeled mathematically into the program so we can’t trust that code 100% that it will do efficient work or what it would have done if you had brought the thing real.”

However, the majority of the participants (20) still used virtual prototypes for testing. Participant 13 described how they successfully used simulation software to test their concept: “We used Comsol multi physics software to test for the temperature with time. With the PBC, it gave a red signal, and it means it wasn’t able to conserve the temperature for much period of time, but then with ABS, it gave a blue, I mean the total border was blue, that means it had a good temperature conserving property."

Participant 9 explained how they used software to collect virtual test results: "Ok because we didn't really build a final working, let me say prototype, we used SolidWorks to simulate maybe the pumping and then the absorption of water by maybe a silica gel. So we saw how the whole thing will be like and then the SolidWorks generated a Word document that is kind of like a report of the testing."

Not everybody was successful using software though, and Participant 8 described how they attempted to test their design through software simulation, but failed because they were not able to create a custom material: "Solid Works to do the testing and then because we chose we selected polymer blending then we couldn't get a blend because if we were to get the blend we were supposed to specify percentages the percentage of say PVC and percentage of ABS and we put it together to have that design but we were not able to."

Not everybody was able to use simulation software. Participant 11 explained how the team used sketches to design a system that allows for maximum airflow: "Yes we did the hand sketches, we did the flow. We kind of tried to use all those ideas here to see and basically that's what actually helped us to come up with the passage of the system where we can get a maximum amount of air flowing in."

Identify functional blocks was the third most frequently reported prototyping best practice behavior, **and** we recorded 18 participants using virtual prototypes and two participants using tangible prototypes. Participant 2 described how working with physical components was helpful in determining how individual functional blocks would fit together: "So I broke it down into different pieces - the glucose monitor right, it's basically made up of two electrodes and these electrodes have some substances that it reacts with glucose and stuff and then it a has a sensor that will monitor or that will give you a reading. So it’s not really a big component right, that’s why it could be made into a watch... Then I had to fit an insulin chamber where it would store insulin and ideally I was trying to get about 300ml… Then I had to talk about the pump because I needed to cause fluid to flow…”

Similarly, Participant 25 described how the team used functional blocks to improve temperature retention in their device: “We looked at [the] specific heat capacity, we realized that when you heat coffee and you put in the mug, the temperature of the coffee doesn’t really drop when it is covered because of the difference of the specific heat capacity of the material and the steel.”

A much larger number of participants (18) used virtual prototypes, and Participant 14 described how they identified functional components, and how this helped the team to visualize the internal functions of a device to detect muscle contractions: “Let just say I’m taking a signal, so how I will acquire the signal? Then my signal processing, do we have [a] notification filter, then I will send a signal. I’m doing SD card, so I‘m doing storage, I’m doing this I’m doing a buzzer. This is my functional structure, like how the internal components work… Now I came to see how the internal working structure was.”

Participant 31 elaborated how the team identified functional blocks, researched already exiting solutions, and finally selected the most suitable approach: “For every function or sub function, I picked a system, I checked out how other people do it. Sometimes I do sketches to show whether this one will work or other ones will work. So let’s say for tying of the condom, I considered… a gear system to lock it up where I can translate my rotational motioning to lock it. For every idea, every sub function, I got about 2 to 3 to 4 means of addressing the function and I compared them using a decision matrix in relation to the objectives or. So I did same for all sub functions and eventually combined them to get what the device is supposed to do."

Participant 3 explained in detail how the team addressed weight and force requirements for their design of a device to help stroke patients with rehabilitation exercises: "If you are going to move the leg with a pulley and you have a person with a maximum weight of 300 pounds, and the leg is going to have this proportion of weight, we used anthropometric data to find which proportion of the weight. So what kind of force are you supposed to apply to move this leg? So based on that, we analyzed the movement of the leg so that if we are you going to use this system then this amount of force and this amount of weight. Is it sufficient or does it meet our user requirement, does it meet our specification?"

3.5 Discussion

3.5.1 To what extent did Ghanaian novice designers' reported behaviors follow prototyping best practices?

The majority of the participants reported using prototypes to ***communicate***. Those who recognized communication as an important function of using prototypes described benefits not only within the team, but also with stakeholders. This reflects studies that have found that engaging stakeholders through prototypes improved communication and accelerated successful product development (De Beer et al., 2009). However, we recorded only seven participants who used prototypes to ***engage with stakeholders*** at the advanced and intermediate levels (one and six, respectively). Engaging with stakeholders is essential for collecting input and feedback throughout the design process to ensure that stakeholder needs are met (Kelley, 2007; Mohedas et al., 2014; Yock et al., 2015), but in this study, participants often used their own experiences and judgments to establish design requirements, evaluate their design concepts, and verify that the chosen design satisfied the defined requirements. While doing this may have seemed practical and convenient, acting as both "judge and jury" is a potentially dangerous practice. A separation of powers, as seen in many governments, provides for checks and balances, and a similar practice is beneficial to design, where its necessary for stakeholders to participate in establishing requirements, designer to develop solutions, and stakeholders to evaluate weather the solution solves their problem (Kelley, 2007; Yock et al., 2015). Only after reflecting on their experiences did participants recognized that they should have engaged with real stakeholders and/or more often to get input and feedback on their design project, suggesting that repeated and reflective practice might be necessary to intentionally use this prototyping best practice behavior.

The second most frequently reported best practice behavior was using prototypes to ***test*** design concepts. This was not a surprising finding since testing a concept is one of the most commonly agreed upon purposes for creating prototypes and a way to verify that the selected concept satisfies established requirements (Dieter & Schmidt, 2012; Yock et al., 2015). Almost all participants realized that they needed to test, but we recorded that more than one third were unable to do so because of the restrictions they faced. A lack of skills and access to resources needed to build and test both physical and virtual prototypes were frequently given as reasons for not engaging on this critical behavior. Based on these statements, it appears that many participants were not prepared to build or test prototypes to the extent that their design project would benefit. The designers who built and tested prototypes frequently mentioned that they either taught themselves, or received help from others to accomplish these tasks. Since the courses required participants to build and test prototypes, adequate training and resources should be provided to ensure that novice designers can leverage this critical design resource.

Eighteen of the participants (8 expert, 10 some evidence) broke up complex designs and ***identified functional blocks***, which is an effective technique used to solve challenging design problems at the component level (Christie et al., 2012; Hilton, Linsey, & Goodman, 2015; Yock et al., 2015). However, only eight of the participants engaged in this best practice behavior at an advanced level, and only four, but not necessarily the same participants, reported later that they ***reassembled the individual blocks*** into a complete model at the end of their project at an advanced level. When looking at related prototyping activities, we found that only nine participants reported the use of prototypes to ***answer specific questions*** (2 expert, 7 some evidence), and none of participants reported using prototypes to ***build the minimal model needed*** at an advanced or intermediate level. While many participants were able to identify and break up concepts into individual components, the prototyping behaviors needed to work at the component level, and bring the functional blocks back together, were underutilized. In other words, participants began the design process well, but missed opportunities to succeed at the component level. Expert designers embrace the approach of breaking up complex design problems and developing component-based solutions. Research by Gerber (2009) has shown that these “small wins” are helpful when facing uncertainty in design, a challenge that many novice designers encounter.

Related to working at the component level and equally crucial to successful design is the practice to ***redefine their design problems***, a behavior that none of the participants reported. Through trial and error, and the iterative use of prototypes, and by building on what has been learned from prior generations, expert designers embrace a problem/solution co-creation process (Kelley, 2010). In other words, what was first perceived as an obvious solution might actually not be the ideal approach. The frequently incomplete understanding that designers develop of the problem space at the beginning of a project can result in a solution that, when implemented, requires a problem statement to be reframed as new information that was not known prior, to only partially, becomes available. Expert designers are aware of and embrace, what Buchanan (1992) refers to as "wicked" problems, and see them as opportunities to develop more refined, and arguably better solutions.

The fact that most participants in this study did not use prototypes to redefine a design problem is concerning, as it represents a missed opportunity for problem iteration, an essential feature of successful design practice. It highlights that novice designers were not aware of what they don't know yet, and instead assumed that defining the problem space once is enough to develop a solution.

3.5.2 What types of prototypes did Ghanaian novice designers use during their project based design courses?

Participants in this study primarily reported the use of virtual tools like sketches, CAD models and simulation software, and we found little evidence for use of tangible prototypes. While both tangible and virtual prototypes are particularly helpful early in the design process to develop and select from a variety of ideas (Brandt, 2007; Campbell et al., 2007; Gerber, 2009; Houde & Hill, 1997; Moogk, 2012), a primary focus on virtual prototypes alone throughout a design project has several limitations. For example, for the most frequently reported prototyping best practice, ***communication***, only five participants used tangible models. Virtual prototypes like sketches often do not include the same information as tangible prototypes, limiting the amount and kind of information that can be transferred between participants. These prototypes leave more room for interpretation and require more domain knowledge from participants to interpret and provide input on a new concept (Authors, 2018). This makes effective communication more challenging and is particularly critical when communicating outside of the design team, i.e. to ***engage with stakeholders***. Some studies have found that, under certain circumstances, virtual prototypes can be equally useful as physical models (Rudd, Stern, & Isensee, 1996; Walker, Takayama, & Landay, 2016), but many researchers agree that physical prototypes produce richer feedback from stakeholders (Brandt, 2007; De Beer et al., 2009; Sauer & Sonderegger, 2009; Wiklund, Thurrott, & Dumas, 1992). Virtual prototypes deprive participants from physically interfacing with a device, and it is often here, when people start "playing" with products, that new insight is gained that can inform design decisions (Kelley, 2010; Sauer, Franke, & Ruettinger, 2008). Since participants reported limited interactions with stakeholders, using tangible prototypes for communication becomes even more important as they can help to maximize stakeholder engagements and improve design outcomes.

Virtual prototypes were used almost three times as often as tangible prototypes for ***testing*** (20 virtual – 7 tangible)**.** While virtual testing is common practice in many domains, it is primarily used to inform physical testing, rather than to replace it (Dannbauer, Meise, Gattringer, & Steinbatz, 2006). This iterative process is challenging, and relies on well-designed models and experienced operators, suggesting that while virtual prototypes can inform physical testing, they should not be considered a replacement for physical testing, unless appropriate methods and expertise are available. The participants in this study reported that a lack of training and limited access to tools and resources prevented them from building and testing physical prototypes. They also reported that it was easier to gain access to CAD and simulation software, and chose this option instead. However, participants also stated a lack of instructions with virtual tools for both building and testing, indicating again that participants were not well prepared for the prototyping tasks expected of them. Studies have shown that access to, and familiarity with, prototyping methods positively impacts project outcome (Camburn et al., 2013), indicating an opportunity for the educators to better prepare students for intentional use of prototypes by introducing them to methods that are easily accessible.

In addition to the actual ***testing*** of the device, participants also described the use of virtual tools like matrices and tables to aid in their decision-making process. This is common practice in design, but establishing the parameters that populate these tables often depends on the use of physical models and stakeholder engagement. Especially when human factors and usability issues of a design are to be evaluated, physical models should to be considered to establish differences between concepts (Kelley, 2010).

For the third most frequently reported prototyping best practice behavior, ***identify functional blocks***, only two participants used tangible prototypes, while 18 used virtual prototypes. While virtual tools can indeed be helpful to identify individual elements of a product, it can be challenging for novice designers to actually work on the component level. This challenge is amplified when virtual models are used since they have the potential to deprive designers of many of the benefits that physical models can afford them with (interaction, testing, human factor evaluation, etc.). The limited CAD skills that participants reported likely contributed to their struggles to successfully use this prototyping best practice to advance their design (Dieter & Schmidt, 2012; Kelley, 2010; Yock et al., 2015).

Across all prototyping behaviors, a lack of training and access to physical resources were given repeatedly as the main reasons for choosing virtual prototypes over physical models. Participants reported that computer software was easier to get access to than physical materials and tools. It appeared however that virtual tools were not an adequate replacement for physical prototypes not only because of their inherent limitations, but also because many participants were not adequately trained and possessed only limited skills with CAD software. This included simulation software, which combined severely limited their ability to create, test and evaluate their designs.

3.6 Limitations and future work

Several limitations of this study could be addressed in future work. The number of participants could be increased for more generalizable results, and include a more equal distribution between female and male participants. Novice designers from different cultural, geographical and disciplinary backgrounds could be included, as well as projects outside of the engineering field. A native member of the participants' community could conduct the interviews, which might contribute to even richer insight into participants' actual experiences.

3.7 Conclusions

We found that participants in this study used some prototyping best practice behaviors like communicate, test, and identify functional bocks well, but underutilized other, critical behaviors like engage with stakeholders and redefine the design problem. We also found that participants in this study reported the predominant use of virtual prototypes and little use of physical prototypes during all stages of design. And while prior studies have found that virtual prototypes can yield meaningful as well as actionable design information (Rudd et al., 1996; Tversky et al., 2003; Walker et al., 2016), the inclusion and iterative use of tangible models is essential, specifically when physical properties like form factors of a design are evaluated (Brandt, 2007; Sauer & Sonderegger, 2009; Wiklund et al., 1992). Physical prototypes have the potential to not only increase communication between designers and stakeholders, but can also generate better project definitions and re-definitions, thereby improving the overall design outcome.

Even though participants referred to limited access and training as reasons for not using physical prototypes more, the virtual models they used instead seemed like poor replacements. Often it appeared that the participants “painted themselves into a corner,” meaning they were able to construct a prototype virtually, but then didn’t possess the skills to evaluate it. The predominant use of virtual prototypes might also have negatively influenced other prototyping behaviors that many experts consider essential, like working with functional blocks, engaging with stakeholders, and redefining the design problem. Some of these best practices hinge on the quick and simple recommendations for using prototypes, and virtual models might not be the best tools for these practices.

It is unclear if participants did not think that they could gain the results they needed from quick and simple prototypes. The availability of high-tech tools such as CAD software and 3D printing technologies might have given novice designers the impression that they need to develop competence with these tools in order to be competitive in today’s job market. However, many experts agree that a quick, simple and iterative use of prototypes allows designers to “fail early” (Collins, 2011; Kelley, 2007). The fact that participants in this study did not recognize the benefits that can be gained from an iterative and repeated use of prototypes to inform design decisions underscores our findings that novice designers lacked intentionality and would benefit from repeated and reflective practice (Adams, Turns, & Atman, 2003; Schön, 1984).

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3.10 Appendix

Table 14 Prototyping best practices

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	Prototypes are increasingly refined and incorporate	Did not refine or incorporate additional	Made refinements and considered incorporation of	Made major refinements to prototype(s), and

refined prototypes.	knowledge gained from previous prototype(s).	knowledge into prototype(s).	knowledge into prototype(s).	incorporated some knowledge gained from previous prototype(s).
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.).

Table 15a) Prototyping best practices, b) The use of virtual and tangible prototypes by Ghanaian novice designers

a)

	Little to no evidence	Some evidence	Alignment with best practice
Communication	5	23	5
Test concepts	12	12	9
Identify functional blocks	15	10	8
Use existing objects	21	10	2
Define design problems	23	7	3
Answer specific questions	24	7	2
Reassemble functional blocks	25	4	4
Engage with stakeholders	26	6	1
Appropriate prototype categories	27	2	4
Iterative refined use	27	6	0
Vary the scale	32	1	0
Multiple concepts in parallel	33	0	0
Inexpensive and early	33	0	0
Refine problem definitions	33	0	0
Minimal model needed	33	0	0

b)

	Virtual	Tangible
Communication	28	5
Test concepts	20	7
Identify functional blocks	18	2
Use existing objects	8	7
Define design problems	9	2
Answer specific questions	10	3
Reassemble functional blocks	5	5
Engage with stakeholders	8	4
Appropriate prototype categories	4	5
Iterative refined use	6	2
Vary the scale	0	1
Multiple concepts in parallel	0	0
Inexpensive and early	0	0
Refine problem definitions	0	0
Minimal model needed	0	0

Chapter 4 Prototyping for context: exploring stakeholder feedback based on prototype type, stakeholder group and question type

4.1 Abstract

Engineering designers frequently use prototypes to gather input from stakeholders. Design guidelines recommend the use of quick and simple prototypes early and often in the design process. However, the type and quality of a prototype can influence how stakeholders perceive a new design concept and can therefore impact stakeholders' responses. Stakeholders differ in experience and expertise and in preparedness for providing responses to designers. In addition, stakeholders from different geographical or cultural settings may respond differently, so the format of a prototype may be even more influential. Existing research has not explored whether different approaches to design prototypes are warranted based on stakeholders, context and setting of a design project. To investigate how the format and quality of prototypes influence stakeholders' responses, we conducted a field study with various medical professionals in Ghana. We presented prototypes for a medical device in different formats and collected responses to the design through semi-structured interviews. We found that professional expertise, prototype format and question type influenced the type of responses stakeholders provided. These findings suggest that designers seeking input from stakeholders on new concepts should consider context-specific prototyping strategies, especially when designing at distance.

4.2 Motivation

Various factors, including visual appearance of a presentation, can influence how individuals perceive the objects or ideas to which they are introduced. For example, companies put great effort into advertisements to entice potential customers to purchase a product. Even though these presentations may not reflect the actual quality or utility, they are critical factors that can impact a consumer's perception and ultimate decision to purchase a product or not (Desmet & Hekkert, 2007; Sauer & Sonderegger, 2009).

Similarly in design, when designers share new ideas with stakeholders – the individuals, groups or organizations that have direct or indirect interest in the product – through prototypes, several factors contribute to how these new ideas are perceived. Prototypes serve as vehicles for designers to communicate their thoughts to others, but the nature and level of refinement of a prototype often depends on the stage of a project (Atman et al., 2007; Christie et al., 2012; Menold, Jablokow, & Simpson, 2017). Prototypes used in the early stages might include conceptual sketches and crude mockups, while prototypes used during later stages might consist of more refined models with virtually indistinguishable properties from a production part (Crismond & Adams, 2012; Hilton, Linsey, & Goodman, 2015).

When reviewing a prototype, not all stakeholders have the ability to look beyond the appearance and form of the presentation and realize the actual benefits and shortcomings of the underlying idea. As a result, promising design concepts can be overlooked because of a less favorable presentation, and less-promising concepts might elicit false-positive responses when stakeholders are presented with a more refined form of presentation (Hekkert, Snelders, & Wieringen, 2003; Leder & Carbon, 2005).

Successful communication and stakeholder feedback may be even more critical for products designed at distance where geographic, time and cultural differences may pose additional challenges to designers (Scrivener, Harris, Clark, Rockoff, & Smyth, 1993). These limitations can especially affect products designed to address the need for global health technologies that benefit people in low- and middle-income countries (LMICs). It is in these settings that the greatest burden of disease can be found, and the development of frugal technology can help meet the medical needs of the world's poorest people (Howitt et al., 2012).

While factors like project setting, stakeholder level of experience, motivation and investment in the project might be difficult for designers to influence, they *can* exercise control over the type and quality of the prototype they share, as well as the questions they ask of those from whom they seek input. It is therefore critical that designers identify the presentation format and question type most appropriate for their stakeholder interaction. In this study we investigated how the type of prototype, stakeholder group membership, and question type influenced the input stakeholders provided.

4.3 Background

Engineering designers often use prototypes as tools for testing and validation, however, multiple studies have shown that prototypes can be useful throughout an entire design process (De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Moe, Jensen, & Wood, 2004; Viswanathan & Linsey, 2009; Yang & Epstein, 2005). The use of design tools typically increases through reflective practice (Cross, 2007; Schön, 1984), and experienced designers often create a variety of prototypes strategically based on the information they seek at a particular point in a project (Kelley, 2007; Ulrich & Eppinger, 2015; Yock et al., 2015). For example, while functional prototypes like 3D-printed models and CAD models are frequently used for functional testing later in the process (Baxter, 1995), designers might use simple prototypes such as sketches and mockups early in the design process to quickly inspire, communicate, elicit input and select from new ideas (Brandt, 2007; Campbell et al., 2007; Gerber, 2009; Houde & Hill, 1997; Kelley, 2007).

In addition to testing and validation, prototypes can be invaluable tools for exploring design details and identifying previously unrecognized issues early in the process (Jensen, Elverum, & Steinert, 2017). Prototypes can be used as tools to facilitate dialog among stakeholders and designers (Bogers & Horst, 2014; Buchenau & Suri, 2000; Goldschmidt, 2007; Mascitelli, 2000; Skaggs, 2010; Stempfle & Badke-Schaub, 2002; Terwiesch & Loch, 2004; Yang & Epstein, 2005), including the elicitation of product requirements from stakeholders, who are considered an integral part of product development (Kelley, 2007; Schrage, 1999; Yock et al., 2015).

Demonstrating ideas to stakeholders through the use of prototypes is preferable to providing a verbal description alone and is especially critical early in a project when designers are developing an understanding of stakeholder needs and wants – often across professional and geographical cultures. In these situations, prototypes can serve as shared objects that support communication, engage stakeholders in the design process, and allow them to better express their opinions and define requirements that designers might not otherwise discover or that can be difficult to synthesize (Jensen et al., 2017; Kelley & Littman, 2006; Scott, 2008).

However, collecting useful input from stakeholders is an activity that novice designers often find challenging, especially when cultural contexts are different and familiar methods and processes do not necessarily translate to a particular setting (Castillo, Diehl, & Brezet, 2012; Mohedas, Daly, & Sienko, 2015). For example, in a study in sub-Saharan Africa, Sabet-

Sarvestani and Sienko (2014) found that the levels of engagement with stakeholders dramatically increased when the team replaced sketches with more refined, physical and functional prototypes. Earlier conversations with stakeholders had not provided critical insight into the cultural viewpoints and concerns about an adult male circumcision device, but when the research team introduced physical prototypes, participants started to interact with the models, compared concepts, discussed differences and provided input about both the concepts and culturally relevant information that would affect implementation if not fully captured in the product requirements. This degree of insight could not have been gathered through interviews and sketches alone; it only transpired through discussions and observations supported by stakeholders' interactions with physical prototypes.

Design experts often call for a minimalistic, or "quick and simple," approach to prototyping, constructing the quickest and cheapest prototype that still satisfies a particular requirement, e.g. the communication of an idea (Kelley, 2010; Moogk, 2012). Low-fidelity prototypes like sketches and mockups are often intentionally simple, incomplete, and sometimes crude representations that convey some critical characteristics of the intended end product. They can be created quickly and inexpensively and allow designers to share and evaluate a large number of ideas. This quick and simple approach enables iteration and decision making early in the design process and the selection of the most promising ideas before much "sunk cost," i.e. time and money, is invested (Houde & Hill, 1997). Fully functional prototypes like 3D-printed models and CAD models that require additional resources such as time, skills and money to create, are typically reserved for later stages in the design process, when functional and/or simulated testing is necessary (Dieter & Schmidt, 2012; Rudd, Stern, & Isensee, 1996). Many design professionals recognize the importance of prototypes for commercial success and follow these recommendations (Lauff, Kotys-Schwartz, & Rentschler, 2017). However, even though prototyping best practices are well understood at a conceptual level, it is unclear the extent to which they are directly transferable or might need to be adapted based on the context, culture, stakeholder characteristics or environment of a design project.

Typically, the level of refinement, detail, and functionality of a prototype increases as designers develop a deeper understanding about the solution space and build on what they learned from earlier iterations (Ulrich & Eppinger, 2015; Yang & Epstein, 2005). Consequently, early prototypes do not always represent the quality and functionality of the intended end product, and stakeholders' perceptions of a new idea might potentially be negatively influenced by the nature and level of refinement of the prototype with which they are presented (Crilly, Moultrie, & Clarkson, 2004; Hare, Gill, Loudon, & Lewis, 2013; Lim, Youn-kyung, Pangam, Subashini Periyasami, & Shweta Aneja, 2006). For example, in a study by Sauer & Sonderegger (2009) examining the influence of prototype fidelity on user behavior, participants were presented with low, medium, and high quality prototypes of cell phones and asked to perform tasks like sending a text message and suppressing a phone number. The researchers found that the more attractive prototypes positively affected user emotions and consequently their judgment of usability of a concept. Kudrowitz (2012) researched how participants judged the creativity of ideas for new toaster concepts. This study focused on one prototyping category — sketches — and found that the concepts represented by the highest quality sketches were most likely to be ranked as the most creative ideas.

Simply increasing the presentation quality and functionality of a prototype, however, does not automatically lead to better input from stakeholders. Recent studies in the field of human-computer interaction concluded that a balance between quality and functionality of prototypes might be most beneficial for the collection of input from stakeholders (Hare et al., 2013; Lim, Youn-kyung et al., 2006). Although studies by Wiklund (1992) and Sauer (2008) have found that low-fidelity prototypes can provide similar evaluation results as more refined prototypes, the authors emphasize that other fidelity dimensions like task scenarios, social and physical circumstances, as well as the participants themselves, can influence stakeholder input. For example, the emotional aesthetic response to an object can directly influence judgment regardless of actual utility of the object. In a human-computer interface (HCI) study with simulated automatic teller machines (ATMs), Tractinsky (2000) found that perceived usability was strongly related to the perceived beauty of a design — the more beautiful participants rated a layout, the more usable they thought it was.

Similarly, Sauer and Sonderegger (2009) have shown that stakeholders' perception of usability of cellular phones was directly linked to how attractive they thought the object was, which did not always correspond to the objectively measured, actual utility of the phone.

Even when the level of refinement among prototypes is similar, members of a diverse group of stakeholders rarely all have the same motivation or experience to comment on a new design (Chamorro-Koc, Popovic, & Emmison, 2009).

In a study evaluating cultural differences of consumer purchasing behavior, Seva and Helander (2009) found that members from one culture (Singapore) focused more on the functionality of the product, while members from another culture (Philippines) valued aesthetics higher when making a purchasing decision. These findings suggests that stakeholders' perceptions and judgments of products might not only be influenced by the nature and level of refinement of a prototype, but also by cultural and perhaps other personal differences among study participants.

An increase in both quality and functionality of a prototype would require more effort from the designer when constructing a prototype but might help stakeholders by requiring less cognitive capabilities or domain knowledge for processing and evaluating information contained in a prototype. For example, Parsons (1989) presented a five-stage model of processing artwork that consisted of favoritism, beauty and realism, empathy, style and form, and autonomy.

Parsons found that cognitive mastering of these stages is linked to the individual's expertise, and that naïve reviewers exhibit a tendency to stereotype based on personal taste. This trend can limit the processing of information, and naïve reviewers might not move through all cognitive stages of the model.

Leder's (2004) five-stage model of aesthetic information processing of artwork (perception, explicit classification, implicit classification, cognitive mastering and evaluation) corresponds with Parsons' model and underscores the fact that it can be challenging to classify, understand and cognitively master artwork successfully.

If, for a moment, we consider low-fidelity prototypes and Impressionist paintings, we notice similarities. Both sketch and painting are incomplete, less precise representations that leave room for interpretation. In contrast, a production-like prototype, or a photorealistic painting, are more complete, contain more information and require little to no interpretation by the reviewer.

Low-fidelity prototypes (or Impressionist paintings) allow for creative interpretation that can lead to insightful input by an experienced reviewer, but lesser trained participants might not be prepared to provide such a response. For instance, Leder states that a naïve reviewer might be satisfied with the perception of Monet's painting "La Gare Saint-Lazare (1877)" as "a depiction of a train station" and terminate the processing of information prior to recognizing important details (Figure 4). The specific content this Impressionist painting reveals to an expert, e.g. the visual properties of light scattered by steam, might go unnoticed by the naïve reviewer (Leder et al., 2004).

These principles of cognition can be applied to evaluating other forms of art (music, literature, etc.) and are equally relevant to what is aesthetically appreciated in the design of everyday objects (Hekkert et al., 2003; Leder & Carbon, 2005). Consequently, this insight into stakeholders' individual domain expertise, and its potential impact on cognitive processing, is important for designers to consider when choosing prototypes to share with stakeholders.

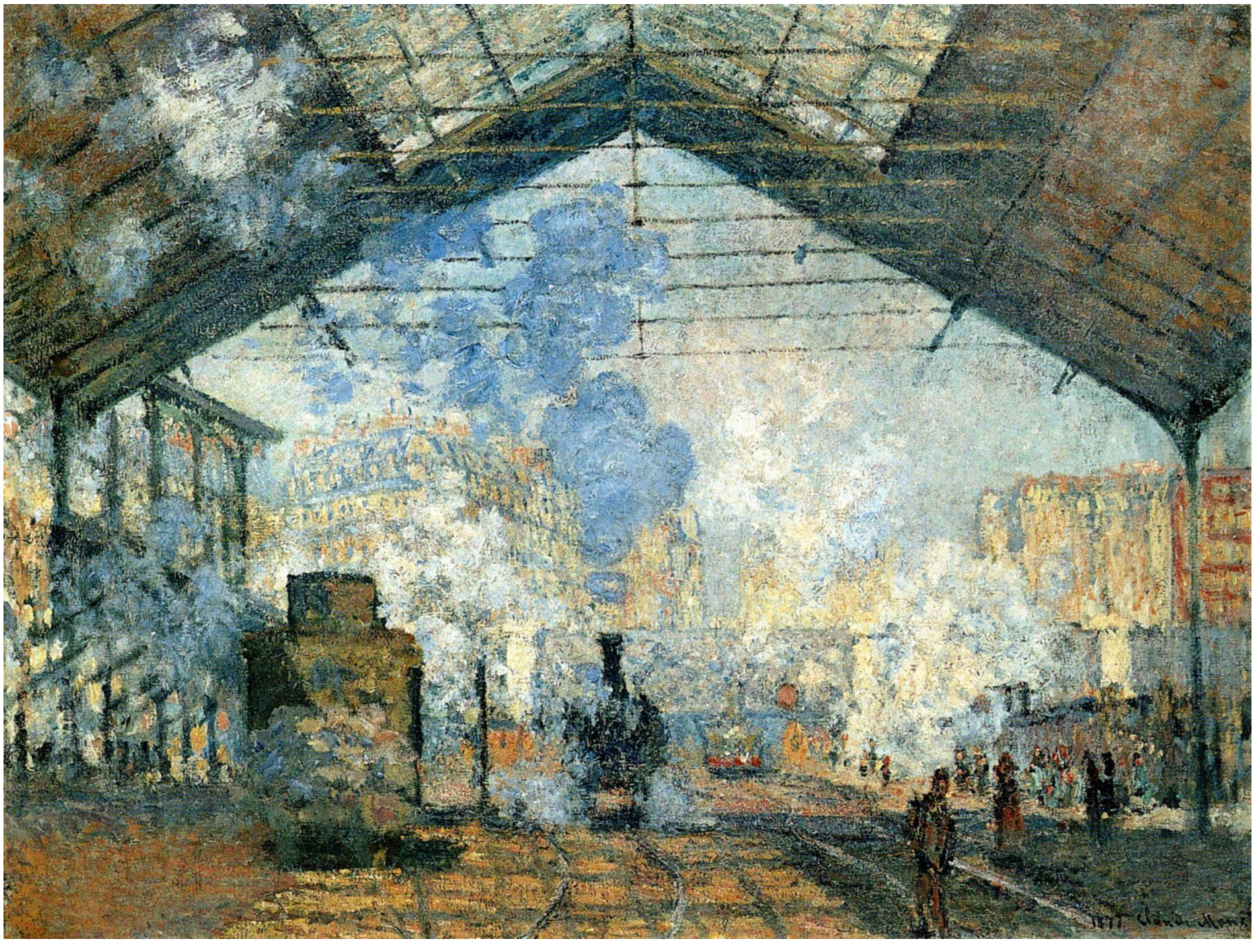


Figure 4 Painting La Gare Saint-Lazare by Claude Monet (1877)

In addition to the influence of domain expertise on cognitive processing, novices in any field tend to have more emotional reactions, whereas experts tend toward cognitive responses that lead to a more analytical way of reviewing an unfamiliar object (Winston & Cupchik, 1992). When a reviewer does not have experience or competency in a specific domain, they may not know how and what to look for.

In studies of novices and experts in physics, Chi, Feltovich, and Glaser (1981) found that the understanding of examples differed based on expertise. For example, novices grouped physics problems together because they included “ramps,” while experts defined a category as “work problems.” These findings illustrate that differing levels of experience and expertise in a domain results in differences in how new examples are perceived.

For novices in particular, being asked for their feedback on design may feel overwhelming, which can lead to frustration and put a reviewer in a negative affective state about how they feel toward the object in question (Frijda, 1989). This negative emotional response then influences the aesthetic experience of how a reviewer processes and evaluates new information (Scherer, 2003).

Scholars in other fields that leverage representations, such as science disciplines, make choices about which representations to use based on context (Daly & Bryan, 2010; Giere, 2004; Grosslight, Unger, Jay, & Smith, 1991; Harrison & Treagust, 2000; Morgan & Morrison, 1999; National Research Council (U.S.), 1996; Seidewitz, 2003). We anticipated that context is also a factor in choosing the type of prototype during a design process, specifically that the type of prototype plays a critical role in the process of gathering input from stakeholders, and that prototyping best practices may need to include adaptations based on the individual stakeholder characteristics and design projects. Additionally, it is well known that interview questions need to be carefully designed to extract unbiased information from stakeholders (Boyce & Neale, 2006; Creswell, 2013; Patton, 2014; Weiss, 1995), and we expected that question type might influence stakeholder responses.

Based on the research team's experience in engineering design, we hypothesized that the recommended, and often effective, “quick and simple” prototyping practices prominent in the literature may not be universally transferable, and that prototype type, stakeholder group and question type may affect design input.

While the study focused on just one product category (medical devices) and multiple stakeholder types (nurses, medical students and medical doctors) in one cultural context (Ghana), the outcomes of this study can contribute to a broader understanding of how prototype type, group membership (stakeholder characteristics) and question type can influence stakeholders’ perceptions of a design concept and the resulting feedback they provide.

4.4 Methods

The aim of this study was to replicate a situation that designers might experience during a project, namely presenting whatever prototype they have at any given point to a variety of stakeholders. We chose stakeholders from a unique cultural context, Ghana, and introduced them to the design of a medical device concept that assists with the insertion of a long-term contraceptive implant. Long-term contraceptive implants are particularly appealing in resource-limited settings where patients have limited access to healthcare providers (Funk et al., 2005). A small polymer rod is implanted into the subcutaneous tissue on the inside of the upper arm of the patient. Properly inserted, the rod releases hormones into the woman’s blood stream and, in contrast to oral contraceptives, does not require regular visits and monitoring by an obstetrician-gynecologist. The implants provide contraception for extended time periods, between three to five years, depending on the manufacturer. However, if not inserted properly, the rod can become embedded in the muscle, restricting efficiency and complicating removal, sometimes even requiring a surgical procedure. Proper insertion is therefore critical and is typically performed by trained healthcare professionals like doctors and nurses. The proposed concept represents a task-shifting device (McPake & Mensah, 2008) that acts as a needle guide (Mohedas, Sarvestani, Daly, & Sienko, 2015). It allows lesser-trained healthcare providers like community health workers (CHWs) to perform correct insertions in rural areas with limited access to healthcare. This simple, low-cost device was first conceived by mechanical engineering students during a capstone design course and is representative of projects in which designers might seek input from a variety of stakeholders, from government officials to rural healthcare workers.

The device concept was presented through various prototypes that are commonly used during design: a sketch, a cardboard mockup, a CAD model and a 3D-printed model, and the questions that motivated the design of this study were:

- How does prototype type influence stakeholder feedback?
- How does group membership influence stakeholder feedback?
- How does question type influence stakeholder feedback?

An experimental research approach was chosen to collect and analyze the data for this study. First, data were collected through semi-structured interviews to gather feedback from stakeholders. Next, the qualitative data were quantified through several analytical methods, and finally, statistical analyses were performed to determine any significance of the findings.

4.4.1 Participants

Forty-five healthcare professionals from a teaching hospital in Ghana were recruited for participation in this study. They included 18 nurses or midwives, 10 medical students, and 17 medical doctors. These participants represented a cross-section of the target stakeholder groups, are likely the most easily accessible respondents to design teams working in similar settings, and would either be using, advising, or training others in the use of the proposed device. The participants were recruited by the family planning department of the hospital and received a small gift for their participation (pen, mini-flashlight or USB memory stick). All participants were aware of long-term contraceptive implants, but none were familiar with the assistive insertion device or had seen it before.

4.4.2 Research design

The research team developed a semi-structured interview protocol to help guide participants through the study. The interview questions were structured in a similar manner to interview questions that designers would use when gathering input from stakeholders (Kelley & Littman, 2006), and the protocol provided a framework that prompted participants to comment on several aspects of the device. It also afforded the interviewer the opportunity to ask follow-up questions when more information was required, or if answers needed clarification. The protocol consisted of nine questions, designed to elicit participants' impressions of the device and to encourage them to critique or add to the proposed design they reviewed. A full list of questions can be found in Table 19 in the Appendix. Prior to collecting the data, pilot interviews were conducted at a large, Midwestern university in the United States to test and refine the interview protocol and the prototypes shown.

Four prototypes were prepared to represent the proposed medical device to stakeholders. These presented a cross section of prototypes that designers commonly create during a design project and included a sketch, a cardboard mockup, an animated (rotating) CAD model and a 3D-printed, production-like representation of the device. The sketch and the CAD model were virtual, i.e. non-physical, representations that were shown either in paper form (sketch) or on a laptop screen (animated CAD model). The cardboard mockup and the 3D-printed model were physical or tangible objects that were given to the participants for examination. The prototypes are shown in Figure 5 below.

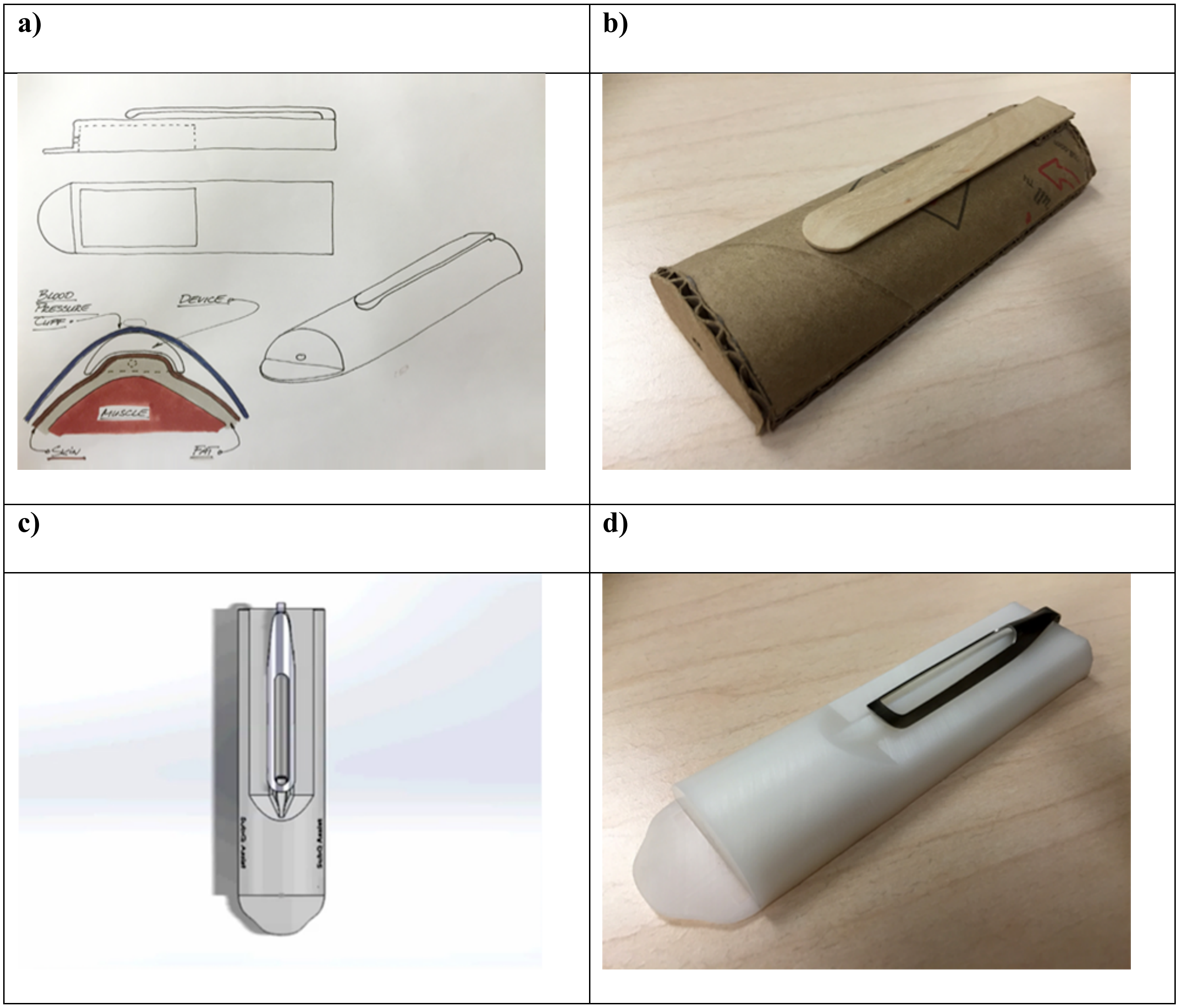


Figure 5 The prototypes used in this study: a) Paper sketch, b) Cardboard mockup, c) CAD model, d) 3D-printed model

4.4.3 Data collection

All interviews were conducted during a one-week period, followed the previously established interview protocol, and were carried out by the same researcher in English. All interviews except one were audio recorded and later transcribed for analysis. One participant did not agree to the use of an audio recorder and handwritten notes of the interview were taken instead.

Each participant was first shown one prototype – either a low-fidelity prototype (sketch or cardboard mockup) or a high-fidelity prototype (CAD or 3D-printed model) – and asked the nine questions in the protocol. Each participant was then shown a second prototype of the same device but from another fidelity group and asked the same nine questions again. Introducing both low- and high-fidelity prototypes to the participants helped to minimize answer biases caused by the nature of the prototypes. The order and type of prototype participants saw were randomly assigned.

4.4.4 Data analysis

After the interview data were collected, the audio files were transcribed for analysis. Three analytical methods were used to determine the usefulness of the answers that stakeholders provided. These included 1) a deductive coding scheme developed by the research team to categorize the type of input elicited, 2) a modified version of the consensual assessment technique (CAT) to capture the quality of the input provided by the individual (Baer & McKool, 2009; Kaufman, Baer, Cole, & Sexton, 2008), and 3) a count of the number of words in participants' responses to each question. To determine if any of the findings were statistically significant, Chi-squared analyses were used for deductive coding of response type, and ANOVA and t-tests were used for CAT and word count analysis.

4.4.4.1 Deductive coding of response type

The research team developed a coding rubric to categorize responses. This rubric consisted of four answer categories as shown in Table 16. Category A answers included design input as part of the response. Here participants provided design input by suggesting for instance that a change in color, size or material should be considered. Category B answers consisted of the participants' opinion backed by justification as to why they felt a certain way. Category C answers comprised unjustified answers that represented the opinion of the respondent only. Category D answers were non-useful and included statements by stakeholders referring back to the design team's expertise rather than giving their own opinion.

Two researchers completed multiple rounds of coding and, once the individual answers were assigned a category, the results were normalized by adjusting the counts to a common scale to account for the different numbers of entries in each group. In a few cases (seven), a single interview question was not asked, and the missing data were removed, resulting in 99% valid answers across all interview questions. The inter-rater reliability for this coding activity calculated with Cronbach's alpha was 0.943 and is considered substantial agreement (Landis & Koch, 1977).

Table 16 Rating rubric for deductive coding of response type

Category	Code	Definition	Example
A	Answer with design input	Provides input / suggestions beyond just answering the question	"So maybe it should be designed in [different] sizes"
B	Justified answer	Answers and explains why	"I like the ability of the device to isolate the skin and then the subcutaneous tissue from the muscle"

C	Unjustified answer	Answers affirmatively but provides no explanation	"Yes" or "No"
D	Non-useful answer	Provides no answer, is unsure or answer was contradicting / made no sense	"I can't say" or “if you get it right then it will work" or "you're the designer"

4.4.4.2 Consensual assessment technique to assess usefulness of response

Another perspective on evaluating stakeholder input is to engage subject matter experts in an assessment procedure called the Consensual Assessment Technique (CAT) (Amabile, 1983; Amabile, Conti, Coon, Lazenby, & Herron, 1996; Baer, Kaufman, & Gentile, 2004; Howard, Culley, & Dekoninck, 2008). This technique, commonly used to rate creative products like paintings and poems, draws on a large number of experts who are presented with multiple artifacts. The experts are asked to rate the artifacts relative to one another on a Likert scale (Kaufman, Baer, Cole, & Sexton, 2008) based on a common criterion like creativity, composition, or use of color. Contrary to the deductive coding approach, the raters are not provided with detailed instructions. Instead, each rater develops their own justification for why they think one artifact should be rated higher, lower, or the same as another. Research has shown that even with the lack of detailed instructions, or a request to justify their decisions, a large degree of agreement can commonly be found among subject matter experts (Amabile, 1983). According to Landis and Koch (1977), a reliability between 0.61 and 0.80 is substantial, while agreements above 0.80 are considered almost perfect. Ideally, a large group of experts (for example 30) would judge a small sample of work (maybe two items). However, it is often not practical, and as a result, a small number of experts are often recruited to evaluate a large body of work (Kaufman et al., 2008).

In order to see if this technique would provide consistent results, we recruited five subject matter experts (designers with several years of experience in product design and/or medical device development) for this activity and asked them to rate the usefulness of the input stakeholders provided. The answers to the individual questions from the first round of the interviews were printed and given to the reviewers in four sets to allow them to physically order the responses. The four sets of data given to the raters consisted of:

- Individual responses to question 3
- Individual responses to question 6
- Individual responses to question 9
- Individual responses to all questions, i.e., the entire transcript of the first round of interviews

Due to the significant amount of time required to complete this activity, the experts were only asked to rate answers from the first round of interviews. The experts were instructed to rate all 45 answers for each of the four sets on a 1 - 5 Likert scale on how useful they thought the answers were for improving the design (with 1 being the least useful and 5 being the most useful). Participants were asked to utilize the full scale (1 - 5) and perform their rating for all four sets of data independently. The raters performed three rounds of ordering for each set to ensure that they were satisfied with their final selection. Raters reported needing between 8 and 10 hours to complete the rating activities. Once the experts rated the data, Cronbach's Alpha was calculated to measure consistency among the five experts. In this study, the agreement was 0.914

across all interview questions and 0.957 for questions 3, 6 and 9, representing significant agreement for all four data sets.

4.4.4.3 Word count

In addition to the previous techniques, a word count analysis was conducted to determine if the volume of words contained in an answer provided any indication of value, here defined as usefulness, of the responses. If so, this technique would require the least effort for analysis, and would be easiest to perform. Thus, we investigated the correlation of word count to the other evaluation techniques.

4.4.5 Questions

Three individual questions were identified during data analysis to explore the potential effects of question type on stakeholder responses. The chosen questions represented distinct areas of interest to inform design decisions: critique of the idea in general (question 3: Do you think this concept would work?), what the patient receiving the implant would think of the device (question 6: How do you think patients would feel about this device being used during the implant procedure?), and finally, if the participants had any device-related design input (question 9: What would you suggest changing about this device?).

4.4.6 Statistical analysis

For deductive coding of response type, the research team performed individual Chi-squared analyses to determine any statistical significance among stakeholder groups and prototype types across all interview questions. Bonferroni corrections were applied to the typical p-value of 0.05 for the individual tests when groups (stakeholders or prototypes) confounded the results. The corrected p-values were: $p<0.016$ for stakeholders (3 groups) and $p<0.0083$ for prototypes (4 types).

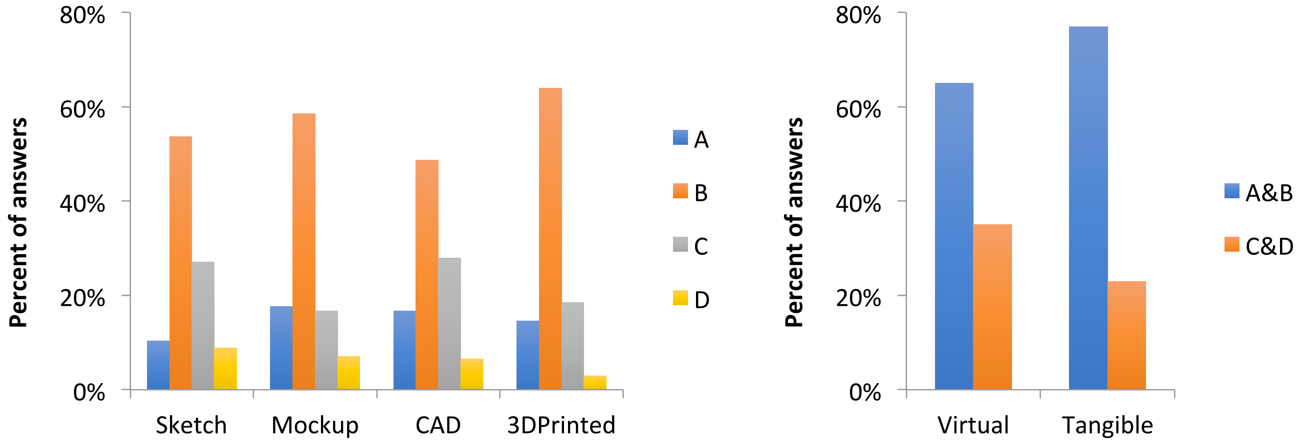
For the results of the CAT, we performed ANOVAs to evaluate if significant differences existed among the categories (stakeholder groups and prototype types). The ANOVAs were followed by t-tests with the same Bonferroni corrections. We also performed ANOVAs and t-tests with the same Bonferroni corrections to determine if word count revealed any significant differences among stakeholder groups and prototype types.

4.5 Results

Here we present key findings that emerged from analyzing the interview transcripts to evaluate how prototype type, group membership, and question type influenced the feedback stakeholders provided. We looked at the feedback for all interview questions first, followed by three individual questions to investigate if the type of question affected stakeholder feedback. Due to the relatively low number of participants and high number of variables in this study, the results from the response type analysis were combined into category A and B answers, and category C and D answers. Additionally, non-physical prototypes (sketch and CAD) were combined into "virtual" prototypes, and physical prototypes (mockup and 3D-printed) were combined into "tangible" prototypes. Collapsing answer and prototyping categories for the response type analysis increased the number of entries in each category and amplified the statistical power for the subsequent analyses. Both CAT and word count produced numerical values and did not require any collapsing. We focused on response type as the primary analytical output and referenced both CAT as well as word count when findings from these methods were significant. We first present the trends of the findings and continue to describe the findings in more detail, including samples of the comments stakeholders shared during the interviews throughout each section.

4.5.1 How does prototype format impact stakeholder input?

When analyzing the responses to all interview questions for prototype format, we observed the following trend: Tangible prototypes (mockup and 3D-printed) provided more category A and B answers than virtual prototypes (sketch and CAD). Naturally, this trend reversed and virtual prototypes provided more category C and D answers than tangible prototypes. A visual depiction of the results can be found in Figure 6.


a)

b)

Figure 6 Results for response category by prototype type for a) individual answer categories, b) Combined answer categories

A Chi-squared analysis of the combined answer categories (A&B, C&D) revealed statistical significance of the findings among prototypes (p=0.000): Tangible prototypes resulted in significantly more category A and B answers than virtual prototypes for all questions (Table 17).

Table 17 Chi-squared analysis of virtual and tangible prototypes

Observed Values between Prototypes

Prototypes	Virtual	Tangible	Total
A&B	341	420	761
C&D	192	118	310
Total	533	538	1071

Expected Values between Prototypes

Prototypes	Virtual	Tangible	Total
A&B	378.72	382.28	761
C&D	154.28	155.72	310
Total	533	538	1071

p=0.0000

The response type analysis revealed that tangible prototypes resulted in more category A and B answers than virtual prototypes. Tangible prototypes resulted in 78% of category A and B answers, while virtual prototypes resulted in 64% of category A and B answers. Analyzing the response data further with CAT and employing ANOVAs and t-tests, we observed the same trend we saw with the response type analysis, but CAT showed no statistical significance. However, we observed larger standard deviations across the two groups with this analysis. A final analysis with word count once again revealed the same trend, also with no statistical significance, and even larger standard deviations (Figure 7).

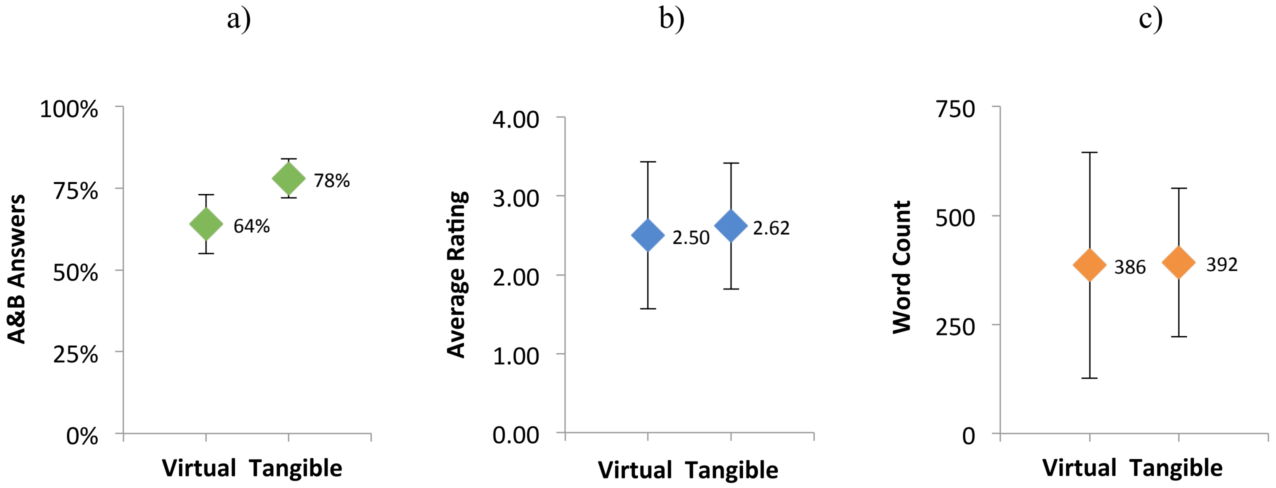


Figure 7 Results for virtual vs. tangible prototypes for a) Response type, b) Expert ratings of usefulness, c) Word count

Participants who reviewed tangible prototypes provided more category A and B answers, higher ratings of usefulness by experts, and lengthier responses than participants who reviewed virtual prototypes. Nurse 16 who commented on a 3D-printed prototype, for example, suggested that the device should be made of a non-rigid material: *"I would love it if it had been more flexible than this."* The nurse also voiced concerns about the device being disposable, and that a way to prevent repeated use, and the inherent risk of cross-contamination, should be considered by the designers: *"Sometimes in our setting, we use it for different patients, so I am thinking that if it will be in such a way that we can use it once for a patient, and that is it. We don't use it for another patient to put the patient at a risk of infection."*

Student 17 suggested that thin patients might not have enough tissue to fill the cavity of the device: *"Maybe when someone is very slim, you may not have this space filled. You may not be able to take a great amount of tissue, just take the upper part of the skin and that will make your insertion partial."* The student expanded on this concern and suggested that the device should be made available in different sizes to fit a variety of patients: "*Maybe there should be varying sizes for different weight measurement… so maybe from 60-70kg you have this. Then from 50-60, you have a smaller one, so that everyone has his or her appropriate size."* The student also proposed a material change that would alter the procedure and give the provider more control: *"Maybe it should be a bit more transparent, so you can see through what you doing, because this, you can't see what you doing. It should be more transparent."*

Likewise, Doctor 28 commented on the material of the device but was concerned about potential allergic skin reactions: *"I think it should be gentle on the skin. If it's an inert material, then that's home and prime, then you don't expect people's skin to react to the material."* The same doctor suggested durable materials to prevent breakage of the device: *"It shouldn't be too* *much of a brittle material that can easily give way. Because if it's in a CHPS [Community-based Health Planning and Services] zone, then you expect this thing to be used, carried from place to place and all of that. If it is something that can easily give way or break, then it may be some minus to it."*

In contrast, the virtual prototypes frequently led to confusion and conflicting information from the participants. For example, when asked if the concept would work as intended, Student 33, who saw a sketch, first expressed trust in the design: *"Yeah it will. Just because of the concept behind it, I think it will,"* but later added that it would have been beneficial to see the actual device, undermining the validity of the previous statement: *"I would have loved to see the device itself, but it's nice. It's really nice. I like the idea. I like everything."*

When participant 25, a nurse who saw a sketch, was asked to comment on the appearance of the device, the input given was: *"It would have been better if I have seen it in reality, this drawing; I can't say much about it."*

Nevertheless, not having enough information did not stop some participants from expressing their opinions. Participant 19, a student, mentioned that the CAD model was *"huge,"* even though the model shown on the screen provided no size reference: *"I think you have to be very careful, when it goes under the skin and I feel it's huge so… I still prefer this [free hand insertion method]."* However, the student later concluded that additional information would have been required to recommend changes to the device: *"I don't really know the parts and everything well, so I can't make a comment on that."*

4.5.2 How does group membership impact stakeholder input?

When analyzing all interview responses for effects of stakeholder group, we found that doctors provided the highest number of category A and B answers, followed by students, then nurses. This trend again reversed for category C and D answers. Here, nurses provided the highest number of category C and D answers, followed by students, and then doctors. The results are shown in Figure 8.

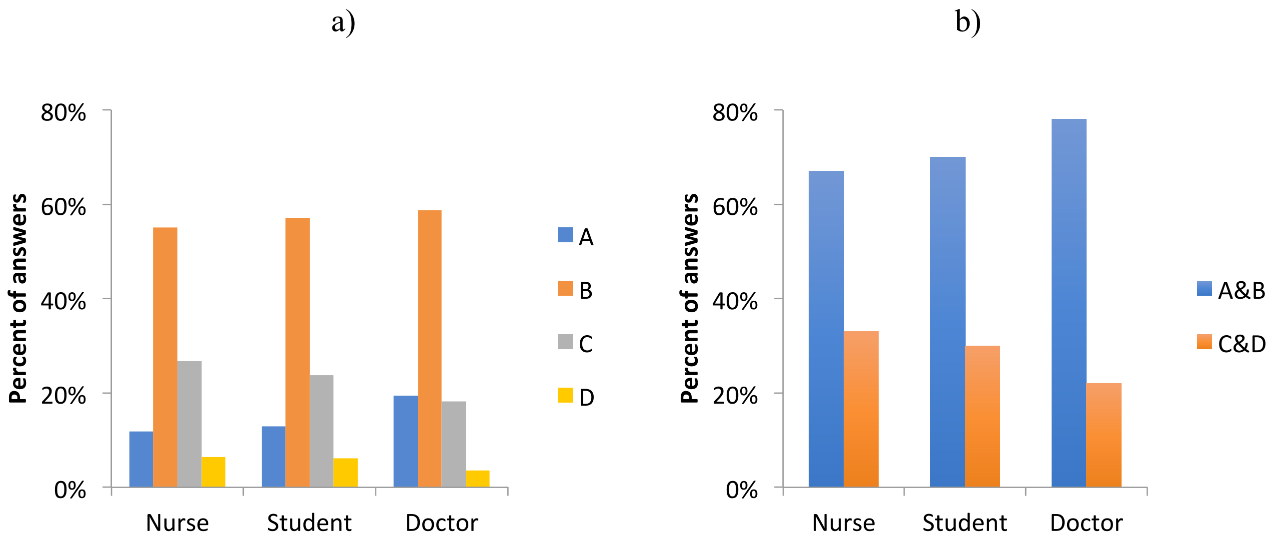


Figure 8 Results for response category by stakeholder group for a) Individual answer categories, b) Combined answer categories

To determine if any of these trends were statistically significant, we used a Chi-squared analysis to investigate differences between the collapsed answer categories (A and B, C and D) and found significant differences (p = 0.0006) among stakeholder groups (Table 18).

Table 18 Chi-squared analysis results for stakeholder group

Observed Values among Stakeholders

Groups	Nurse	Student	Doctor	Total
A&B	284	162	316	762
C&D	145	78	91	314
Total	429	240	407	1076

Expected Values among Stakeholders

Groups	Nurse	Student	Doctor	Total
A&B	303.81	169.96	288.23	762
C&D	125.19	70.04	118.77	314
Total	429	240	407	1076

p=0.0006

The response type analysis showed that 78% of the responses provided by doctors were categorized as A and B answers, followed by 68% of A and B answers for nurses, and 66% of A and B answers for students. CAT analysis of usefulness by experts revealed the same trends, but none of the results were statistically significant. We did however observe larger standard deviations for all stakeholder groups with this technique. While word count did not show any statistical significance, it also revealed that doctors had the highest average word count. However, nurses had higher word counts than students with this analysis, but with a much larger standard deviation (Figure 9).

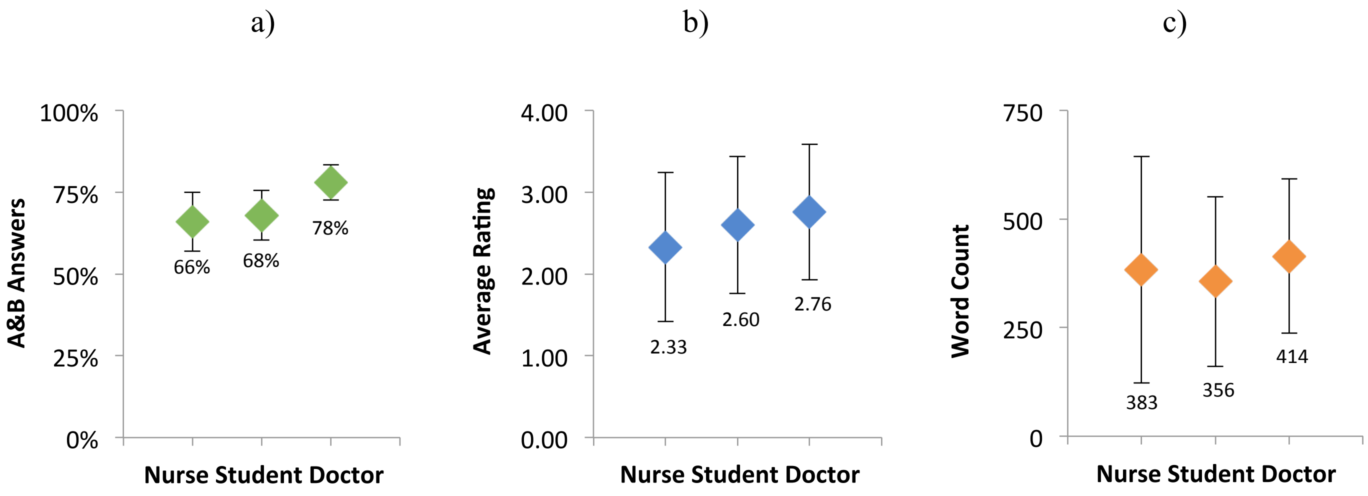


Figure 9 Relationship between stakeholder type and a) Response type, b) Expert rating of usefulness, c) Word count

Doctors provided the highest number of category A and B answers, the highest ratings of usefulness by experts, and the longest responses among the participants. For example, Doctor 38 thought that the presented concept was appropriate, but voiced concerns about patients' perceptions regarding the size of medical devices: "*Generally patients are scared when they see big things… So if things are portable, so just… like this. This is small, so I think it's ok.*"

Doctor 11 who saw the cardboard mockup expressed concerns that the tissue might actually not move into the cavity as intended and suggested that the designers might investigate how the skin behaves during the procedure: *"You actually have to apply some, a little bit of counter traction on the skin so that the skin is actually not creased or folded. So how sure are we that we don't get that?"*

Finally, Doctor 36 stressed the importance of safety and the fact that the device should be disposable to avoid cross-contamination among patients: *"If it's going to be disposable, then I guess it will be safe to use. Because it's… invasive with the device… a little blood spillage, unless you plan on disinfecting and sterilizing after each patient."*

Students and nurses also provided category A and B answers, but fewer than doctors. Student 20, who reviewed the cardboard mockup, was concerned about the size of the device, but focused more on how the size might influence the procedure: *"I kind of think it's too big… it's going to be like bulky in between the person's arm, so if you could have something smaller than this, but with the same concept, I think it's great."*

Student 23 compared the appearance of the 3D-printed device to an everyday object and posited that it would put a patient at ease: "*It looks… seriously, it doesn't look like something that is used to insert an implant; it's rather like an opener. Yeah, a bottle opener or something… It does not look like it's going to be used in the hospital."*

Similarly, Nurse 26 associated the 3D-printed prototype with a writing utensil and concluded that it would be non-threatening: *"It's just like a pen case. It looks like a pen case, so there is no problem with this."*

Nurse 14 thought about how the device would integrate into the implant procedure and stressed the need for training of the service provider to put the patient at ease: *"We should [have]* *adequate training on how the device would be used. Training of the facilitators, and then let the client know how it would be used on them. They would buy into the idea."*

Overall, nurses provided the lowest number of category A and B answers and the lowest ratings of usefulness by experts across all questions and prototypes. For example, when Nurse 5, who reviewed the 3D-printed prototype, was asked if the concept would work, the answer was referred back to the design team's earlier description of the device's intended use: *"You said it can do that."*

4.5.3 How does question type impact stakeholder input?

To investigate if the feedback differed among individual questions, we examined the results of our analysis methods for all stakeholder groups and prototype types for questions 3, 6 and 9.

4.5.3.1 Questions and stakeholders

First, we examined if there were significant differences among stakeholder groups for questions 3, 6 and 9, and then we investigated each stakeholder group separately. We found statistically significant differences based on the outcomes of response type analysis (p=0.0000) between questions 6 (most category A and B answers) and question 9 (least category A and B answers) for all stakeholder groups. For question 6, 89% of the responses were categorized as A or B answers, while only 54% of the responses to question 9 were categorized as A or B answers. For question 3, 73% of the responses were categorized as A or B answers. Following this analysis across all stakeholder groups combined, we investigated the differences among the three questions within the individual stakeholder groups. We found that nurses provided significantly more category A and B answers (p=0.0001) for question 6 (97%) than for questions 3 and 9 (64% and 47%), respectively.

Overall, doctors provided the highest percentages of category A and B answers across the three stakeholder groups, and offered significantly more category A and B answers ($p=0.0032$) for both questions 3 and 6 (88%) than for question 9 (56%).

An analysis of student responses showed no significant differences among the three questions, and neither CAT nor word count resulted in any significant findings for questions or stakeholders. The statistically significant findings are shown in Figure 10:

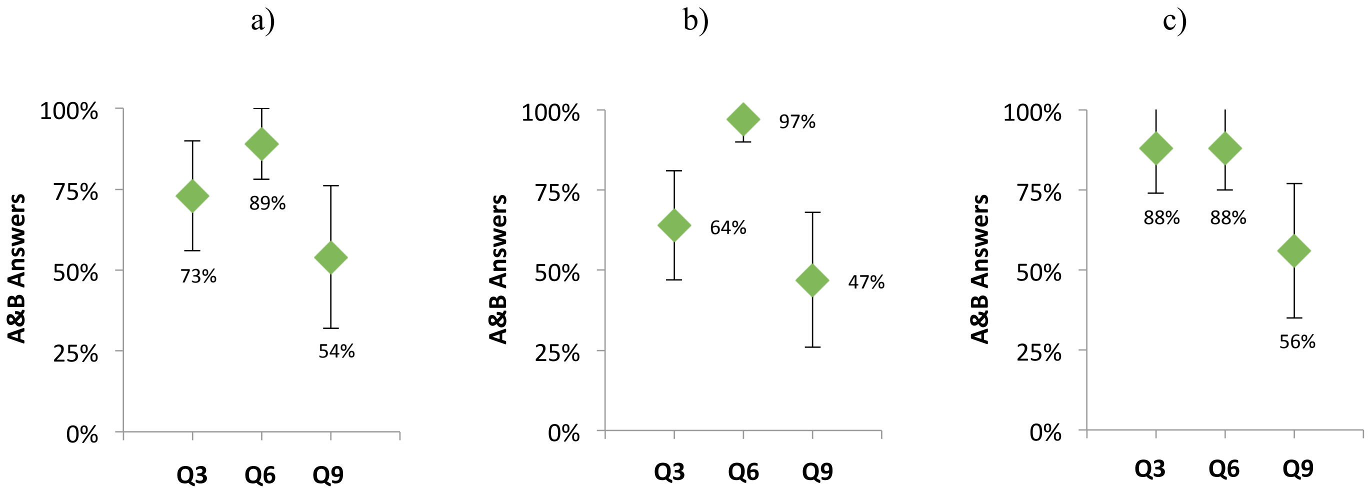


Figure 10 Results for category A and B answers for questions 3, 6 and 9 for a) All stakeholders, b) Nurses, c) Doctors

All stakeholders were significantly more likely to provide category A and B answers for question 6 - "How do you think patients would feel about this device being used during the implant procedure?" than for question 9. For example, Nurse 8 thought that not seeing the needle during the procedure would be an asset to the patient: "*Once she doesn't see the needle directly, it will rather make her more relaxed. You explain the procedure to her and how this thing is going to work on her, that will relax her…*" Nurse 16 mentioned a concern about the rigidity of the device: "*As I said, it's a bit hard so the patient will feel a bit uncomfortable.*" Nurse 24 appreciated what the device would do for the medical provider, but was concerned about the patient: "*For us doing the insertion, it will be easy, but thinking about the patient, I think it will be a bit uncomfortable.*" Nurse 25 suggested that after a brief explanation, the patients would be fine with the procedure: "*Just like you check their BP, you wrap a cuff around their arm, they will be comfortable once you've explained the procedure to them.*" Nurse 43 voiced concerns about patient comfort and asked if the designers had considered this already: *"I don't know whether there would be some discomfort when the tissues are going there, [do] you anticipate that?"*

In contrast, question 9 resulted in the lowest number of category A and B answers across all stakeholder groups. For example, Doctor 9 had only this to say: "*I think it's fine,*" while Doctor 11 was uncomfortable commenting on technical details: "*Wow you're talking to me [about] engineering…*" Doctor 6 who saw a sketch of the device expressed a need more information to make any recommendations: "*I am wondering how it's going to lift the skin under the cavity, so until I see it, I can't comment.*"

4.5.3.2 Questions and prototypes

When investigating if question type influenced answer category, usefulness, and length of response by stakeholders, we found statistically significant differences (p=0.0000) between virtual and tangible prototypes for question 9. We categorized 78% of the responses to tangible prototypes as A and B answers, while only 24% of the responses to virtual prototypes were categorized as A and B answers (Figure 11). We also observed this statistically significant difference between virtual and tangible prototypes when assessing for usefulness of the feedback with CAT (p=0.0002), while word count analysis showed the same trend but no statistical significance (p=0.3507) and large variation.

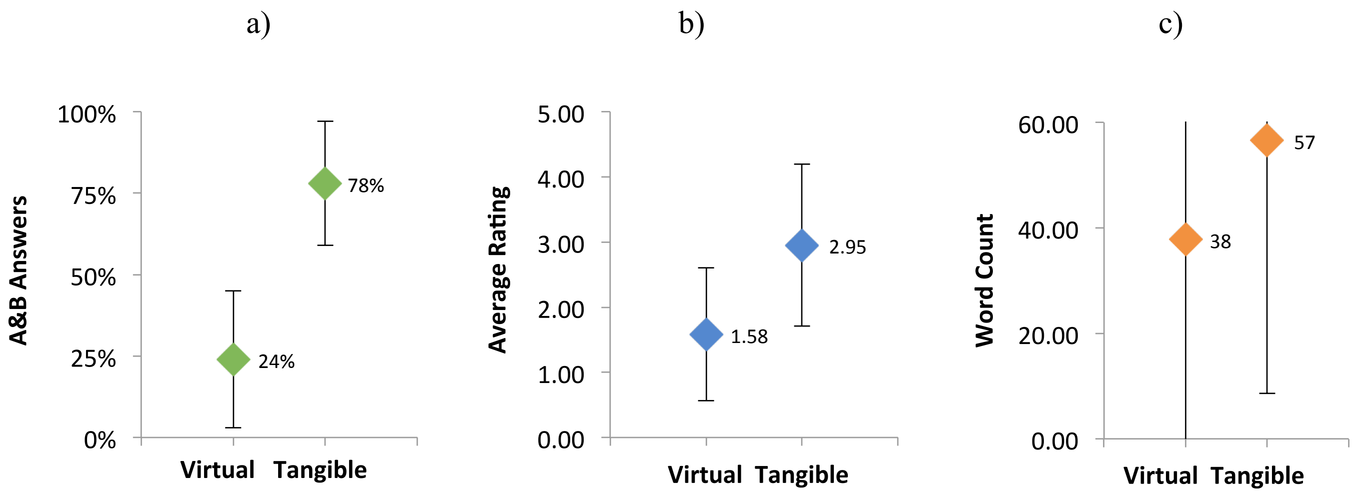


Figure 11 Results for question 9 between prototype types and a) Response type, b) Expert rating of usefulness, c) Word count

Stakeholders who saw tangible prototypes when answering question 9 "What would you suggest changing about this device?" responded with more category A and B answers, higher ratings of usefulness by experts, and lengthier answers than those who reviewed virtual prototypes. For example, Nurse 4 who saw the cardboard mockup mentioned: "*I like it, but I think the size is a little big. Yeah, if it can be a little [more] portable, that will be fine.*" Doctor 10 was even more specific about how the size of the device might be critical to a diverse patient population: "*Maybe there should be some form of adjustment to take care of thin people because it may accommodate more than the skin in the subcutaneous tissue. It may take some amount of muscle, so maybe some modifications should be made for thin people.*" Nurse 16 who commented on a 3D-printed prototype added concerns about the disposable nature of the device: "*Yes, it's enough to know it disposable, but unfortunately, for our setting, sometimes, due to inadequate consumables and all, we turn to reuse it. So if it can be done in such a way that you can't reuse it…*"

In contrast, virtual prototypes resulted in fewer category A and B answers, lower ratings of usefulness by experts, and shorter answers for question 9. For example, Nurse 1 did not think that the proposed concept was realistic enough to comment on: *"I can't say much about it until I start using it or something."* The nurse later added: "*I think for now no because this is just on paper.*"

This was echoed by Doctor 6 who questioned if the device would actually work and wanted to see the actual device perform: "*Ok I haven't seen it actually been done before, so I am wondering how it's going to lift the skin under the cavity. So until I see it, I can't comment.*"

4.6 Discussion

4.6.1 Influence of prototype format on stakeholder feedback

In our examination of how prototype format influenced the feedback stakeholders provided, we found that tangible prototypes provided more category A and B answers, higher ratings of usefulness by experts, and longer responses than virtual prototypes across all stakeholder groups and questions. These findings echo recommendations that call for tangible prototypes to be used for collecting stakeholder input on products and devices (De Beer et al., 2009; Kelley, 2010; Otto & Wood, 2000; Schrage, 1999), but other researchers have found that, depending on the task, virtual prototypes can be equally beneficial during product development, as long as designers are aware of their benefits and limitations (Rudd et al., 1996; Ulrich & Eppinger, 2015; Walker, Takayama, & Landay, 2016).

The variations in the types of responses, ratings of usefulness by experts, and word count were smaller for the cardboard mockup and 3D-printed model, making them and the resulting input more predictable and easier to synthesize for designers than the sketch and CAD model. The larger variations we recorded in the types of responses, ratings of usefulness by experts, and word count within the virtual prototyping categories suggest greater diversity in participants' ability to respond to these prototypes and likely make the process of synthesizing input more difficult for designers. Several participants stated they were not able to obtain enough information from the virtual prototypes, which in some cases, resulted in unjustified or non-useful feedback (category C and D responses). Limited experience with, and exposure to, the design process, medical device development, or the review and critique of virtual prototypes might have contributed to the perceived need for additional information. As a result, stakeholders might have felt overwhelmed by the task, which could have led to frustration and emotional responses rather than analytical processing of information (Frijda, 1989; Scherer, 2003; Winston & Cupchik, 1992).

Our study also differentiated between low- and high-fidelity representations within the categories of virtual and tangible prototypes. We found that within each category, the high-fidelity prototypes (CAD model for virtual, and 3D-printed for tangible prototypes) were related to more category A and B answers, higher ratings of usefulness by experts, and lengthier responses. These results align with Brandt's (2007) findings that higher levels of detail within a prototyping category led to smaller variations and more focused conversations between stakeholders and designers. Similarly, studies evaluating stakeholder feedback on new product concepts have found that the highest level of prototype quality correlated with higher ratings by the stakeholders regardless of the criteria, e.g. functionality or creativity of an idea (Häggman, Tsai, Elsen, Honda, & Yang, 2015; Kudrowitz et al., 2012; Sauer & Sonderegger, 2009).

In contrast, some studies found little difference between low- and high-fidelity prototypes, but these tended to focus on non-tangible, two-dimensional products like user interfaces and web sites only (Lim, Youn-kyung et al., 2006; Walker et al., 2016). In our study, the low-fidelity prototype categories led to larger variations and more confusion in the stakeholder feedback. For example, one nurse asked which one of the views of the sketch to comment on, not realizing that all views of the sketch depicted the same product.

Similarly, even though participants were made aware they were looking at a prototype, some still voiced concerns about properties specific to a particular prototype, such as the fact that the blood of a patient might stain the cardboard material used for the mockup. This insight might indicate that some participants were not able to look beyond the prototype format and its inherent limitations when assessing low-fidelity representations.

4.6.2 Influence of stakeholder group membership on stakeholder feedback

In our examination of group membership, we found differences among stakeholder groups. The feedback doctors provided included the most category A and B answers, the highest ratings of usefulness by experts, and the longest responses. The feedback students provided included more category A and B answers and higher ratings of usefulness by experts than nurses, but nurses provided longer responses than students. There might be several reasons for these differences. First, the introduction of “design thinking” to a clinical environment is a fairly recent development (Kalaichandran, 2017; Roberts, Fisher, Trowbridge, & Bent, 2016) that is often limited to physicians and medical students, and frequently exclude nurses (Rosen & Ku, 2016). Therefore, many healthcare professionals, including those in this study, likely had limited experience with the design and development of medical devices.

Further, nurses in African countries have traditionally been trained with a focus on physician order execution and task completion (Marks, 1994). The mission-style training approach, adopted by many sub-Saharan African countries from the British colonial system (Edwards, 1957), might have introduced a social desirability bias, where nurses are not necessarily accustomed to providing critique and voicing their opinions. More recently, efforts have been made to redefine nursing practices from a more task-oriented approach to one of caring for and caring about patients (Savage, 1995) but without necessarily challenging the hierarchal structure within the healthcare system. These factors might explain why nurses performed better on the patient-centric question than on the design-specific question.

On the other hand, the training of Ghanaian medical doctors often includes fellowships in the United Kingdom and the United States (Klufio, Kwawukume, Danso, Sciarra, & Johnson, 2003), introducing them to a culture of innovation and critique. This international experience might explain why doctors provided the most category A and B answers to questions addressing the design of the medical device used in this study.

Nurses frequently provided less critical observations and instead compared the presented device to everyday objects. Leder defines these “looks like” or “feels like” responses as prototypicality, a cognitive way for a reviewer to associate a new object with another and more familiar object. The association of information content with their own situation and emotional state can lead a reviewer to be satisfied with this simple recognition. Parsons (1989) posited that “A naïve perceiver might be satisfied with the recognition of the train station in Monet’s La Gare Saint-Lazare because ‘he likes trains because they remind him of a journey.’” This observation is not limited to art, as differing levels of expertise influence how new concepts are perceived in other domains as well. While experts tend to abstract principles when solving a problem, novices often focus on literal features (Chi, Feltovich, & Glaser, 1981). In our study, we saw indications that an emotional evaluation, association with a familiar product, and focus on features might have limited cognitive inquiry by a reviewer. Several participants compared the device concept to everyday objects like a bottle opener or pen case and concluded that since these objects are safe, non-threatening devices, a medical device concept that looks or feels similar must therefore share similar qualities.

Similar to studies that showed that stakeholder input can be contradicting, making it difficult for designers to synthesize information (Mohedas, Daly, & Sienko, 2014; Scott, 2008), we, too, found evidence of sometimes conflicting stakeholder input. Even when participants' feedback consisted of category A and B answers, high ratings of usefulness by experts, and lengthy responses, their input was sometimes incompatible. For example, one stakeholder asked for the device to be transparent so that practitioners can see what they are doing, while another stakeholder appreciated the fact that an opaque device would hide the needle from the patient during the implant procedure. Both participants provided useful input, yet suggested opposing product qualities (transparent vs. opaque). The fact that these arguments could both be valid underscores that designers cannot simply take stakeholder input at face value. Instead, designers should expect contradicting feedback, especially early in the design process, when seeking comprehensive understanding of the requirements. Prototypes provide a chance to interact with, and evaluate, proposed solutions and can be used to help uncover "unknown unknowns" (Jensen et al., 2017). Designers need to embrace these findings and use them to inform prototyping strategies and design decisions.

Our results align with studies that have shown that physical prototypes were more widely understood by and accessible to stakeholders, positively affected user emotions, and prompted stakeholders to responded with a high degree of confidence (De Beer et al., 2009; Häggman et al., 2015; Sauer & Sonderegger, 2009). Our results also reflect Björklund's (2013) findings that the mental representations of design experts were broader, more detailed, and more geared toward problem solving. Similarly, we saw indications that stakeholders who might have been exposed to innovation and critique in addition to training in medical practice and patient care (Klufio et al., 2003; Sienko, Kaufmann, Musaazi, Sarvestani, & Obed, 2014) might have been better prepared to provide feedback on the design and development of new products, here medical devices.

4.6.3 Influence of question type on stakeholder feedback

In our examination of how question type influenced stakeholder feedback, we found that the feedback stakeholders provided depended on the question type as well as on stakeholder characteristics. Several studies have shown that the questions designers ask are contingent on the phase of the design process (Christie et al., 2012; Menold et al., 2017). Combined, these findings suggest that designers need to consider the questions they ask as well as whom they are asking, regardless of where they are in the design process. Not all stakeholders seem to be equally able to provide input to all questions, and designers may need to rephrase a question, or situate it in a different context, depending on whom they are engaging with. Through the question type, designers can, and need to, enable stakeholders to relate to the design problem and feel comfortable enough to respond.

For example, we found that question 6 “How do you think patients would feel about this device being used during the implant procedure?” resulted in the most category A and B answers across all stakeholder groups. Particularly, nurses provided the most category A and B answers for this patient-centric question that was situated within the stakeholders’ knowledge domain of treating and caring for patients. By no longer asking stakeholders to critique the device directly, this question took them out of the “hot seat” and allowed them to assume the role of caregiver, associating with their patients. This new perspective enabled stakeholders to talk more freely and comment on the experiences both patients and caregivers might have when using the device during the contraceptive implant insertion procedure. To reference Leder's example again, question 6 may have enabled stakeholders to pick up on the nuances only an expert could, such as "the visual properties of light that is scattered by the steam" in Monet's painting (Leder et al., 2004). Here, familiarity and experience may have allowed stakeholders to move through several stages of information processing for this question, evaluating the device on a much deeper level than before and thinking through the procedure from the patient and caregiver perspectives. For this particular question, stakeholders had become experts, and the highest number of category A and B answers we recorded for this question reflected this level of expertise.

We also found that question 9, "What would you suggest changing about this device?" resulted in the lowest number of category A and B answers for all stakeholders and all prototypes. Two reasons come to mind for why this question might have fared so poorly: First, it was asked last and participants might have exhausted their input on the previous eight questions and simply gotten tired of repeating themselves. Second, this question asked participants directly what they would change about the design. Since some participants had little or no experience with medical device design, this might have caused them to feel uncomfortable and/or overwhelmed. As the findings from other questions indicated, participants were more likely to provide input when they were asked about specific details rather than to give general input. This is another important finding, since novice designers tend to ask more general questions. Our findings suggest that not all stakeholders are equally prepared to do this; designers need to consider their stakeholders and carefully select and frame questions that enable participants to provide feedback on the proposed design.

4.6.4 Influence of analytical methods on stakeholder feedback

When comparing the findings of the different analytical methods employed during this study, all three techniques identified similar trends: Tangible prototypes led to more category A and B answers, higher ratings of usefulness by experts, and longer responses than virtual prototypes. All techniques also revealed that doctors provided more category A and B answers, higher ratings of usefulness by experts, and longer responses than students, who provided more category A and B answers and higher ratings of usefulness by experts than nurses. Nurses provided longer responses than students, but with large standard deviations and no statistical significance.

In addition, there were a few other noteworthy observations as well. For example, the categorization of responses by type identified the highest number of statistically significant differences among prototypes and stakeholder groups. This finding is not surprising since this method relied on carefully developed codes to analyze the data. The codes provided specific criteria for the analysis and therefore revealed the most precise distinctions among the input categories. The iterative development of codes, in addition to several rounds of coding, required a substantial time commitment from the researchers. Despite these efforts, the results suggest this method led to the most insightful, significant, and reliable findings.

The CAT relied on criteria individual raters established by themselves (Amabile, 1983), and we observed the same trends as with the categorization of responses by type when analyzing the results. At the same time, the larger standard deviations and less significant results of this analytical method make the findings less reliable for eliciting stakeholder input. The small number of expert raters who participated in the analysis likely contributed, and more experts might improve the results.

Word count used no other criteria than number of spoken words and showed less pronounced, and sometimes even conflicting, trends with no statistical significance. This analytical method also resulted in the largest standard deviations that occurred where we noticed mismatches among the techniques. In one extreme case, when examining the influence of prototype type on question 9, the standard deviation of 54.75 words even exceeded the average count of 37.79 words for virtual prototypes, large enough to question the validity of this result.

We also found that for all participants, nurses had the highest word count for question 9, but fewer than expected category A and B answers and the lowest average ratings of usefulness by experts for this question. In contrast, doctors had the lowest word count, but the most category A and B answers and second-highest ratings of usefulness by experts for the same question. In these cases, the word count results were in opposition to the findings of the other techniques. These observations contrast with Blumenstock's study (2008) that found a positive correlation among the length and the quality of articles published on Wikipedia. However, such articles are peer-reviewed and nominated, a process that is absent when collecting stakeholder input. In summary, how much a person says seems not to be a good indicator of quality of content, making word count the least reliable analytical technique we used.

4.7 Implications

The findings of this study are important for both novice and expert design practitioners in general and in particular for distant design projects when access to stakeholders can be challenging. Specifically in global health design, where geographic distances and time-zone differences can limit and restrict conversations, interactions with stakeholders need to be carefully planned and executed. Here, a successful prototyping strategy is even more critical and should encompass the following elements:

First, designers must select appropriate prototype types. For example, when looking for procedural or in situ feedback, simple prototypes like sketches might not enable stakeholders to address issues that a functional prototype might reveal (Sauer et al., 2008). The commonly accepted prototyping best practices (quick and simple) used in the United States are not necessarily universally transferable and need to be adjusted to the unique context and background of the design project. It is not enough to consider that different stages in the design process call for different types of prototype (Atman et al., 2007) – designers also need to select the most appropriate prototype types that allow stakeholders to best respond and provide useful input.

Second, designers need to recognize that not all stakeholders are equally prepared to respond to all prototypes – a sketch might work well for an engineer but not resonate with a social worker. When stakeholders have limited domain experience, or feel inadequately equipped to evaluate a new concept, they might not be able to move through the stages of information processing necessary for a comprehensive evaluation. Instead, they might feel overwhelmed and express an emotional response that can be misleading and even harmful, especially when the designers are not experienced synthesizing the feedback they receive. Designers need to recognize who their stakeholders are and select the types of prototype that best support these groups.

Third, the questions designers ask when using prototypes need to be carefully selected to enable dialog between stakeholders and designers. Designers need to consider the context of the question and develop questions that enable stakeholders to more effectively draw upon their expertise. A stakeholder who is not well prepared to provide technical input might be an excellent candidate to offer insight into the social or psychological impact a new design concept might have on a community. Having experience with the use of a device is not the same as having experience with the design and development of a device. It is up to the designer to ask the “right” questions and take advantage of individual stakeholders' expertise.

Fourth, the findings can inform design pedagogy and curriculum development (Authors, 2017), since the application of the results might not be limited to medical device design. They might be transferrable to other products, services or systems where designers use prototypes to gather stakeholder input. In this study, prototype type, stakeholder group and question type all influenced stakeholder feedback. Educators can capitalize on this insight and guide students to carefully consider the unique circumstances of their design project. In particular, they can encourage students to develop prototyping strategies that optimize their interactions with stakeholders when looking for feedback on new design proposals.

4.8 Limitations and future work

There were several limitations to this study that could be addressed in future work. Only a subset of the answers participants provided was analyzed in detail, and the number of participants could be expanded. The study was limited to one unique setting and stakeholders with limited cultural, geographical and professional background variety. Future studies might explore the extent to which the findings can be transferred to different stakeholder groups, prototypes of products in other arenas, as well as systems and processes. The questions used during the interviews represent typical questions that designers might pose to stakeholders, and were not explicitly designed or selected to specifically study the effects of question type on response type. A male researcher who was not a native of Ghana conducted all interviews and, although English is considered an official language, it might not have been the first language for some participants. These factors might have influenced the participants’ responses specifically .

4.9 Conclusions

We found that tangible prototypes resulted in more category A and B answers and higher ratings of usefulness by experts than virtual prototypes. We also found that higher fidelity prototypes led to more category A and B answers and higher ratings of usefulness by experts than lower fidelity prototypes. Designers need to be aware of this tendency and should proactively develop context-specific strategies that complement the "quick and simple” approach to prototyping, since prototype type matters. We also found that in general, participants with more domain experience provided the most category A and B answers and the highest ratings of usefulness by experts as compared to participants with less domain experience. This was however not true for all questions, and certain groups responded with more A and B answers and higher ratings of usefulness by experts to some questions than others. Questions positioned within a stakeholder’s professional domain resulted in more category A and B answers and higher ratings of usefulness by experts than general and technical questions. It is therefore important for designers to carefully consider what questions they ask, and to whom they are asking them. Specific rather than general, or summative, questions that are situated in a participant’s domain have the potential to empower stakeholders to comprehensively evaluate the prototypes with which they are presented.

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4.12 Appendix

Table 19 Interview questions

1) In general, what do you like about this concept?
2) What do you dislike about this concept?
3) Do you think this concept will work?
4) Do you think the device would be easy or hard to use?
5) Do you think the device would be safe to use?
6) How do you think patients would feel about this device being used during the implant insertion procedure?
7) What do you think about what the device looks like?
8) Do you think this device would be appropriate for CHPS workers (Community based Health Planning and Services) to use in rural settings?
9) Based on what you know about this concept, what would you change about this device?

Chapter 5 Discussion: Contributions, implications and future work

5.1 Summary

5.1.1 Chapter two summary

Chapter two reported on a study of how novice designers in the United States used prototypes during design, referred to as study 1. First, an investigation of the participants' conceptions of prototypes showed that they were more limited than the reported, actual use of prototypes. Most participants considered prototypes to be almost exclusively physical models even though all participants used non-physical or virtual models. Even though only three participants mentioned that prototypes could be used for communication, all of them reported using them for this activity. Although none of the participants produced a completely finished model by the end of their project, only three participants defined prototypes as incomplete models early on. In summary, participants seemed not aware of their own, broad use of prototypes and required prompting to realize the frequency and spectrum of prototype uses. As a result, participants did not fully conceptualize the broad uses and values of prototypes, even after just having completed a semester long design course.

Our investigation included participants' reported use of prototypes. Findings showed that 'test and evaluate' was the most frequently cited prototyping behavior. This was not surprising, as testing is a prominent use of prototyping in design. Additionally, this activity was also required by the course structure. Using prototypes for communication, on the other hand, was not required, but used by all participants. Even though experts agree that simple prototypes like sketches can be ambiguous and leave much room for interpretation, the novice participants in this study reported that even simple and unrefined prototypes afforded more precise conversations and transfer of knowledge between team members and stakeholders. Contrary to experts who often use prototypes early to help establish requirements for a project, novice designers primarily used prototypes later to share their progress and get feedback / seek affirmation. Even though participants engaged stakeholders, engagement often occurred later in the design process and all participants recognized that they should have used prototypes earlier and more often to engage with stakeholders.

Since the findings indicated a broad use of prototypes, we developed a framework for using prototyping to better evaluate how the reported behaviors of novices compared to prototyping best practices. We found that participants' reported prototyping behaviors aligned well with several best practices. This included testing, answering specific questions, and iterative use to refine prototypes. However, many prototyping behaviors lacked intentionality, quality and frequency, and most participants did not use prototypes strategically. Several suggested reasons for this limited use included: not enough time, limited resources and varying degrees of personal skills and abilities to fabricate and test prototypes.

5.1.2 Chapter three summary

Chapter three reported on a study of how novice designers in Ghana used prototypes during their semester long design course, referred to as study 2. This study built on the findings of the previous study and we applied the same prototyping best practice framework for evaluating the reported prototyping behaviors. We found that participants followed several prototyping best practice behaviors, and the most frequently reported behavior was communication. Almost all participants used prototypes for communication, but few only a few participants used prototypes to engage with stakeholders, particularly early in the design process when they established user requirements. Often, participants used their own experiences and judgments to establish design requirements, and later evaluated and verified that the chosen design satisfied those requirements. However, almost all participants recognized this as a shortcoming and realized that they should have engaged real stakeholders earlier and more often. Limited time and physical distance were given as reasons for not engaging with stakeholders.

The second most frequently reported prototyping best practice behavior was “testing a concept” and about two thirds of the participants used prototypes to test concepts. Most participants realized that they needed to test, but some were unable to do so. Those participants reasoned that a lack of educational background and training resulted in them not possessing the personal skills needed to perform testing of their prototypes. They also claimed that limited access to both physical and virtual resources hindered their abilities to construct and use prototypes.

The third most frequent prototyping behavior we recorded was “Identify functional blocks.” More than half of the participants identified functional blocks of their designs, but less than a quarter reassembled the individual blocks into a complete model. Similarly, only nine participants answered specific questions and none built the minimal model needed. With this behavior, the participants began by identifying functional blocks, but did not work at the component level to answer specific questions and did not bring the individual blocks back together. These findings represent missed opportunities, specifically to succeed at the component level through “small wins.” Notably, none of the participants reported that they used prototypes to redefine their design problems. Many experts agree that allowing the solution to a problem to change as more becomes known about the problem (problem-solution co-evolution) is an essential part of successful projects, but participants in this study did not do this.

We also investigated what types of prototypes participants used. We found that participants primarily used virtual and very few tangible prototypes for the reported prototyping best practice behaviors. For example, for “Communication” we recorded a 5-28 ratio (tangible/virtual), Testing: 7-20 and Engage with Stakeholders: 4-8. The reasons given for the limited use of tangible prototypes included a reported lack of instructions for prototyping fabrication, limited access to and experience with prototyping fabrication, and a lack of access to physical resources. Participants claimed that it was easier to gain access to virtual tools like computer software than to physically fabricate models, but that they did not receive training that prepared them to build and test either virtual or physical prototypes. The limited skills with CAD software that participants reported resulted in compromised abilities for building and testing of virtual models, and the test results might have been potentially wrong or misleading.

5.1.3 Chapter four summary

In Chapter four, we discussed our study of how prototype format, stakeholder group, and question type influenced stakeholder feedback, referred to as study 3. We used three analytical methods to evaluate the results. These methods included a deductive coding scheme we developed to categorize the type of input stakeholders provided, a modified version of the consensual assessment technique (CAT) to capture the usefulness of individual answers, and a word count in participants’ responses to each question.

When looking at how prototype format influenced stakeholder feedback, we found that tangible prototypes resulted in more category A and B (useful) answers, higher ratings of usefulness by experts, and longer responses than virtual prototypes across all stakeholder groups and questions. The same findings applied to high-fidelity versus low-fidelity prototypes. We observed smaller variations with tangible prototypes, making it potentially easier for designers to synthesize the information provided by stakeholders. Several stakeholders felt they did not get enough information from virtual prototypes. Even though participants were told that they were reviewing a prototype, some still had concerns about the properties of the low-fidelity models, i.e., blood staining the cardboard model.

When looking at stakeholder group, we found that doctors provided the most category A and B (useful) answers, highest ratings of usefulness by experts, and longest responses. Students provided more category A and B (useful) answers and higher ratings of usefulness by experts than nurses, but nurses provided longer responses than students. Nurses performed best on the patient centric question, but did not believe they had much to contribute to the design of a new medical device. We found that stakeholders who were exposed to a culture of innovation and critique might be better prepared to provide feedback on design and development of new products. We also found indications that stakeholders without this experience tended to associate information with something familiar to them. Several participants compared the prototype to everyday objects like a bottle opener or pen case. These “Looks like” or “feels like” responses led to conclusions that since these objects are considered safe, non-threatening devices, a medical device concept that looks or feels similar must therefore share similar qualities.

We also found that question type influenced stakeholder feedback. The question “What would you change about this device?” resulted in the least number of category A and B (useful) answers, while the specific, patient centric question “How would patients feel about this device being used?” resulted in most category A and B (useful) answers.

Regarding the analytical methods used in this study, we found that all three techniques identified similar trends. Categorization by answer type relied on carefully developed codes to analyze the data and identified the highest number of statistically significant differences, producing the most insightful, significant, and reliable findings. Consensual Assessment Technique (CAT) resulted in larger standard deviations and less significant results. The small number of expert raters likely contributed to these findings, and a larger group of experts might improve results. Word count had the largest standard deviations that in some cases exceeded the average word count. We found that how much a person said was not a good indicator for quality of content.

5.2 Discussion

The work presented here leveraged several concepts from multiple disciplines to develop a better understanding of novice designers' intentional use of prototypes and how prototype type influences stakeholder feedback. Our findings indicate that novice designers lacked intentionality for using prototypes and underutilized them throughout the design process, including to engage with stakeholders. Our results further showed that factors such as prototype type, stakeholder group, and question type all influenced stakeholder feedback.

5.2.1 Scoping, defining and redefining the problem

Among the behaviors that novice designers underutilized was the scoping, defining, and redefining of the problem-solution space, as evidenced in Studies 1 and 2. When defining a problem, expert designers often engage stakeholders to develop an understanding of their needs and wants, and develop requirements based on their input (De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Kelley, 2007; Moe, Jensen, & Wood, 2004; Schrage, 1999; Yock et al., 2015). Ideas of possible solutions can then be evaluated against these requirements, and quite frequently, projects change direction as possible solutions are reviewed by stakeholders and "unknown unknowns" are discovered (Jensen, Elverum, & Steinert, 2017). This process of problem-solution co-evolution, that often includes "wicked" problems (Buchanan, 1992; Horst W. J. Rittel & Melvin M. Webber, 1973), can be frustrating for novices, but experienced designers embrace such opportunities to improve solutions as they develop a deeper understanding of the "real" problem.

Using prototypes for redefining the problem-solution space and developing multiple concepts in parallel was evident in studies 1 and 2. In study 1 we noticed that some participants in the United States made minor refinements like changes in technology (using a shape memory alloy instead of an actuator, for example), but we saw little to no indication that study 1 participants rethought their solution approach in its entirety. Participants in study 2 reported few engagements with stakeholders and when they did share information with stakeholders, it most frequently occurred later in the process to share and elicit feedback on solutions the teams had conceptualized. Since problem redefinition is often triggered early and by stakeholder feedback, this might explain why we saw little to no problem redefinition by Ghanaian novice designers.

Time restrictions and course requirements likely contributed to the lack of problem redefinition. Yet, not engaging stakeholders and allowing for multiple, iterative solutions informed by stakeholder feedback early in the design process poses the risk of developing a design that does not in fact solve the "real," underlying problem, and instead addresses a perceived and possibly unverified need.

5.2.2 Quick and simple use of prototypes

Across Studies 1 and 2, students did not emphasize quick and simple prototypes or create multiple prototypes in parallel. Many experts embrace this practice of using several quick and simple prototypes to identify design problems early and learn from small failures (Kelley, 2010; Kordon & Luqi, 2002). Gerber argues that creating and visualizing multiple ideas through low-fidelity prototyping allows the designer to "reframe failure as an opportunity for learning," supporting progress and strengthening one's beliefs about their own creative ability (Gerber & Carroll, 2012). Many advocates suggest that prototypes should be created early and be used iteratively throughout the product design process (Yock et al., 2015) and Kelley calls prototyping "the shorthand of innovation" (2010). This is supported by Schrage's argument that "wasting prototypes" is essential for detecting errors and discovering opportunities" (Schrage, 1999). Following these guidelines for "quick and dirty" prototyping allows designers to create multiple solutions for fast evaluation and without investing large amounts of "sunk costs," i.e., time and money (Houde & Hill, 1997). With respect to intentionality, the quick and simple creation of prototypes has the potential to help designers find answers efficiently and early to advance the design. But the creation of simple prototypes without considering the specific answers the designer seeks might not necessarily provide information or reveal required changes.

One of the inherent benefits that the fabrication of quick and simple prototypes can afford is the sharing and evaluation of ideas without investing a large amount of sunk cost. We did not however, see much evidence for this prototyping best practice behavior across studies 1 and 2. Most participants focused on prototypes that represented a more complete, final solution, and did not often create many primitive or incomplete models.

The participants in the United States frequently used 3D printing as a form of prototyping. The introduction of this technology has raised the bar for what we expect from prototypes by supporting the quick and relatively cheap creation of high-fidelity prototypes that can appear similar to a final product. Instead of a cardboard mock-up for example, designers can now quickly present stakeholders with production-like parts. These models might however give stakeholders the impression that the design is nearing completion and that there is little opportunity for them to suggest changes, which is not conducive to gathering stakeholder feedback.

Additionally, when novice designers send CAD files to a 3D printer, they are often skipping the process of designing and iterating on individual features and components, such as push or pull handles, hinges, and ergonomic features (i.e., "Let's just build the whole thing as is"). So while 3D printing has the potential to greatly accelerate and improve the quality of prototyping, if not used intentionally, it might deprive novice designers of the "knowing in action" (Schön, 1984) and hands-on interaction with models that the creation of quick and simple physical prototypes can afford.

5.2.3 Virtual vs. physical prototypes

We found that novice designers who participated in Studies 1 and 2 from the United States and Ghana used virtual prototypes to a similar extent, but novice designers in Ghana did not use tangible prototypes frequently. Since novice designers in Ghana are likely limited in their access to resources, we expected to find simple, physical prototypes constructed from locally available materials. Instead, Ghanaian novice designers primarily developed virtual prototypes that required the use of computers and computer aided design (CAD) software. These novice designers noted that they weren't well trained in the fabrication of physical models, and had limited access to resources for fabricating physical prototypes. They also stated that computers and virtual tools were easier to access. Some of these novice designers also thought that in order for them to get a job or be recognized for their work outside of Ghana, they needed to be fluent in more sophisticated tools like CAD and finite element analysis (FEA). However, a conversation with an instructor revealed that rough prototyping materials were available, i.e., scrap materials and low cost items from the market, but novice designers did not use them and instead preferred virtual tools and software (Author, personal conversation, March 16, 2018).

Although virtual tools are frequently used in design, there are several limitations to non-physical prototypes. While virtual tools can enable designers to quickly create models and iterate, they can also be misleading if designers are not aware of their limitations and use them deliberately. For example, it can be challenging to get a sense of scale from reviewing a CAD model that might be extremely large on a small computer screen. Performing certain human factor evaluations on virtual prototypes, like determining how comfortable an object feels or the forces required to open a latch might be close to impossible with virtual models (De Beer et al., 2009; Kelley, 2007). But even beyond these more obvious limitations, virtual models contain additional risk factors. For example, when used for testing and evaluation, designers might use simulation software to determine the strength of a particular part. However, the simulation is only as good as the setup, and many experts agree that it can be challenging to accurately simulate a real world testing scenario (Dannbauer, Meise, Gattringer, & Steinbatz, 2006). Here, physical tests are often performed to not only inform virtual simulations, but also to verify that the simulation performs in a similar manner as the physical test. The simulation will only perform as programmed, and setting up a comprehensive test can be very challenging as it is potentially easy to overlook aspects that might be critical to the outcome.

Almost all participants in studies 1 and 2 acknowledged their limited experience with virtual tools. When designers have limited experience with testing, and with virtual testing in particular, it is possible that the test results might have been incomplete, misleading or even false. A novice might not realize that they forgot to include certain parameters in their simulation, and take the positive outcomes as confirmation for their proposed design. While virtual tools have become easier to access and operate, they require caution when used, and educators should train and guide students to avoid false positive results as possible outcomes of poorly designed CAD models and simulations.

When investigating how prototype type influenced stakeholder feedback, we found that stakeholders responded with more useful feedback when presented with tangible prototypes. In addition to the limitations mentioned above, not all stakeholders were used to reviewing virtual prototypes. Designers, and in particular engineering designers, might be familiar with reviewing and visualizing a design proposal that is for example presented as a wireframe model, but others might not share this familiarity. It is therefore advisable that designers consider whom they are presenting their prototypes to, and if a particular person is not experienced reviewing virtual models, a different prototype format might be better suited to support the sharing of an idea.

There could be several reasons why novice designers in Ghana largely focused on the use of virtual prototypes. During design, physical prototypes are often rough and unrefined since they focus on a specific aspect of the design rather than the finished product and it might take a particular mindset to overlook the sometimes unfinished appearance of such prototypes. Cultural influences as well as aesthetic preferences might provide some insight.

In many sub-Saharan African educational systems, including Ghana, students are required to pass qualifying exams to advance to the next level of schooling (Glewwe, 1996; Glewwe & Jacoby, 1994; U.S. Embassy in Ghana, 2018). This focus on memorization likely teaches students to be good test takers by the time they enroll in college, but might compromise on other, more exploratory learning approaches that embrace failure as a way to learn. Students might be taught that there is a “right” solution to a problem, and they might not be familiar with an iterative approach to problem solving that builds on what has been learned from prior iterations and that design experts often recommend (Kelley, 2010; Kordon & Luqi, 2002; Yock et al., 2015).

Specifically in Ghana, traditional sculptures often depict human bodies with muscular, symmetrical and polished features (Clarke, 2006), and such sculptures seldom appear abstract or unfinished. Similarly, Ghanaians appear to appreciate refined attire that includes traditional rich colors and bold patterns as well as western fashion trends, and Ghanaians can rarely be observed in casual clothes like shorts or ripped jeans (Leaf TV, 2018; Schwimmer, 2017). Combined, the early educational focus on memorization of "right" answers and an appreciation for refined, polished appearances of objects might create a unique cultural context that might impact the prototyping preferences of study participants in Ghana -- both designers who create, and stakeholders who evaluate those prototypes. Instead of creating quick and simple models, novice designers might have opted for CAD models that appear more finished and refined rather than a quick and simple but unrefined physical prototype, and stakeholders might have been influenced by the appearance of some prototype types when evaluating a concept.

Another reason Ghanaian students favored virtual prototypes might be the relative newness of their discipline in Ghana (University of Ghana, 2018). Biomedical engineering might not yet be fully established and recognized as professional practice (Bediako, 2014), and some educators might have had limited or no hands-on or industry experience. This potential lack of professional experience, combined with a focus on the "right way" of doing things might explain why instructors and course deliverables favored prototypes that appeared more professional, polished and more complete (i.e., computer generated models and drawings) than exploratory mock-ups that might lack refinement. As a result, novice designers may have made prototyping choices that favored virtual models. Exposure to how engineering design is practiced outside of Ghana, and outside of the academic environment, might help educators and students appreciate the benefits that a quick and simple approach to prototyping can afford.

5.2.4 Creating prototypes to engage with stakeholders

Almost all participants used prototypes to communicate and engage with stakeholders but few did so intentionally. Because some of the participants in study 1 worked on projects with stakeholders in different geographical and cultural contexts, they sometimes found it challenging to communicate and keep their stakeholders involved. In such cases, good communication is especially critical because designers likely understand even less about stakeholders' circumstances, needs, wants and requirements (Mohedas, Daly, & Sienko, 2014; Sarvestani & Sienko, 2014). Without the intentional use of prototypes to elicit information from stakeholders, novice designers are at risk of developing solutions that meet their perceived requirements but not necessarily those of their stakeholders.

We hypothesized that the motivation for creating prototypes should be driven by a question, i.e. a purpose. Having one or more particular questions in mind can inform the type and level of prototype refinement that is best suited to answer said questions. This might include considerations about with whom the prototype is shared, here the stakeholders. As our third study showed, depending on stakeholder group, one type of prototype might be better suited than another to enable participants to provide feedback. When prototypes are created to answer a technical question for example, designers might not consider it crucial to engage with stakeholders. For example, when working on a dialysis machine, a designer might be solely interested in pumping performance and details such as volumetric output, power consumption and life cycle of the pump. However, being aware that a patient might be impacted by the noise the pump emits while sitting next to the machine for hours might inspire the designer to select a quieter pump.

Specifically in educational settings, Seshadri (Seshadri, Reid, & Booth, 2014) found that engineering design projects have evolved and now often require knowledge outside of purely mechanical systems. Studies 1 and 2 have shown that novice designers often do share these prototypes with stakeholders to collect feedback. The highly functional prototypes that are created to solve a technical problem are not necessarily well suited to communicate ideas, and specific types of prototypes might be more successful when engaging with stakeholders, which many agree is essential for successful design (Kelley, 2010; Schrage, 1999; Yock et al., 2015).

5.2.5 Prototypes and communication

Across studies 1 and 2 we also observed that novice designers underutilized prototypes for communication, which many experts recognize as a critical behavior. In *Serious Play* (1999), Schrage argues "prototyping is probably the single most pragmatic behavior an innovative firm can practice." The author continues to explain that beyond troubleshooting and problem-solving, physical models provide a fundamentally different way of communicating around a "shared space" — the prototype. Prototyping affects both internal and external communication and makes it easier for clients to articulate what they want by interacting with a prototype.

Good communication is especially important when sharing ideas across professional, geographical and/or cultural contexts, to help designers more fully understand and address the intended product's objectives and stakeholders' real needs (Houde & Hill, 1997; Sugar, 2001). Many of the participants in studies 1 and 2 worked on projects with stakeholders from contexts different from their own, making interactions challenging, Not intentionally creating prototypes to support communication might have led to missed opportunities for gathering stakeholder feedback.

Many participants found it challenging to engage with stakeholders, and sometimes reported using themselves, or teammates, as stakeholders instead. When the same person establishes the criteria, develops the solution, and then judges the design against those criteria, the “checks and balances” that are commonly applied to ensure successful design are lacking. Since designers are working for their stakeholders, designers should intentionally engage with them and, when they do, be strategic about how they use prototypes to elicit feedback. Even though some participants did not engage with stakeholders during their project, upon reflection during our interviews, most participants realized and articulated the importance of doing so. Repeated, reflective and intentional practice may support their future use of prototypes to engage stakeholders throughout the design process.

Prototypes can also facilitate communications among the design team members and have been recognized as a point of focus for design teams (Edelman et al., 2009; Schrage, 1999; Stempfle & Badke-Schaub, 2002). This matches what many participants in our studies experienced as well. One of the study participants reported that after the project team saw its first physical prototype come off a 3D printer, it was like "having a baby," and the entire team experienced a new wave of motivation and excitement about the project. The presence of physical models excited the participants, made them proud of their work, and pulled the team together with increased commitment to the project. Prototypes also can facilitate communications with educators, as another participant reported: "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…” Many participants were surprised by how prototypes improved communication within their design team and with their instructional team. Their surprises might suggest that they were not intentional in their use of prototype to communicate, which possibly deprived them of what Gerber calls "small wins" (Gerber, 2009).

We observed that many novice designers frequently used prototypes without intentionality and underutilized prototypes throughout the design process, specifically to engage with stakeholders. However, many experts agree that prototypes can influence how stakeholders perceive ideas and that not all stakeholders respond the same way to all prototypes (Desmet & Hekkert, 2007; Sauer & Sonderegger, 2009; Tractinsky, Katz, & Ikar, 2000). If designers do not intentionally plan how they use prototypes to engage with stakeholders, they might present prototypes that are not well suited to support feedback elicitation sessions and stakeholders might not provide the input needed to make well-informed design decisions.

5.2.6 Prototype type

We saw evidence that participants in studies 1 and 2 made different prototype choices. In study 3 we found that different prototype types influenced stakeholder feedback, which aligns with findings from other researchers (Crilly, Moultrie, & Clarkson, 2004; Hare, Gill, Loudon, & Lewis, 2013; Lim, Youn-kyung, Pangam, Subashini Periyasami, & Shweta Aneja, 2006; Sauer & Sonderegger, 2009). We observed that physical prototypes (mockup and 3D-printed models) resulted in more usable feedback from stakeholders than virtual prototypes (sketch and CAD models) and high-fidelity prototypes (CAD and 3D-printed) resulted in more usable feedback than low-fidelity prototypes (sketch and mockup). These findings present an opportunity for designers to intentionally select prototype formats and levels of refinement that are well suited to support their stakeholders to provide feedback, but also pose a potential risk: If two ideas are shown using prototypes of different types or levels of refinement, stakeholders might favor a particular prototype, regardless of the underlying concept or idea (Kudrowitz, Te, & Wallace, 2012). Understanding this risk is particularly important for novice designers to take into account, since they often do not intentionally prepare prototypes specifically for stakeholder presentations. As a result, they might inadvertently create a variety of prototype types and levels of refinement that could result in false-positive or positive-false-negative feedback from their stakeholders.

We found that some novice designers relied heavily on virtual prototypes in study 2, yet our results from study 3 suggested that virtual prototypes may not be well-suited to support conversations with all stakeholders. For example, one of the Ghanaian novice designers remarked that a particular stakeholder would not be able to respond to an engineering drawing. It is unclear if the nature of the low-fidelity and virtual prototypes itself may have discouraged Ghanaian novice designers from more frequent interactions with stakeholders. However, a more intentional use of prototypes might have led the participant mentioned above to create a different prototype that would have better supported communication with the stakeholder who they did not expect to be able to respond to an engineering drawing.

5.27 Question type

In study 3 we found that stakeholder feedback was sensitive to question type. Stakeholders responded with the most useful feedback when they were asked about details that were situated within their domain of expertise. For example, by not asking stakeholders to critique the proposed medical device concept directly, they were taken out of “hot seat” and talked more freely about their experiences.

However, novice designers typically do not match their prototypes or questions to the stakeholder and instead base their inquiries on where they are in their current design process (Christie et al., 2012; Menold, Jablokow, & Simpson, 2017). In studies 1 and 2 we found that the prototyping behaviors of novice designers often lacked intentionality, suggesting it unlikely that they deliberately thought about question type when sharing prototypes with their stakeholders. Doing so would likely have impacted the responses stakeholders provided, and designers should be aware of how the questions they ask can influence stakeholder feedback. Designers should consider their audience and prepare questions that make stakeholders feel comfortable and empower them to provide constructive feedback. This might include rephrasing a questions or situating them in different contexts in order to better enable stakeholders to relate and respond to prototypes and design questions.

5.2.8 Intentional practice

Our results from studies 1 and 2 suggest that even though engineering practice is intentional (Sheppard, Colby, Macatangay, & Sullivan, 2006), and participants in our studies had prior experience with project based design courses as well as the creation of prototypes, the simple repeating of a behavior did not lead to intentional practice. Studies by Dickinson and Gollwitzer have found that habits are formed by repeated practice (Dickinson, 1985; Gollwitzer, 1999), but repeated practice alone does not make one an expert. Research in fields outside of engineering have shown this also to be true, and suggest that deliberate practice has the potential to transform novices into experts (Chi, Glaser, & Farr, 1988). These findings extend even beyond intentional practice and suggest that, in addition to practicing with a purpose, it also matters how one practices. Ericsson (1993) argued that to become a true expert or elite performer, one needs to practice deliberately for at least a decade. While undergraduate curricula cannot and are not designed to elevate students' performance to expert level, the encouragement of intentional and deliberate practice could help guide novice engineering designers in their use of prototypes.

Educators could introduce deliberate or intentional practice by encouraging novice designers to ask specific, often component-level based questions that a prototype might help answer. The prototype could be specifically constructed to answer these questions, with novice designers only building what is needed in order to preserve resources such as time and money. Then, novice designers might reflect on what they did, and how successful they (and the prototype) were in getting the feedback desired and addressing the question they originally asked.

The interviews in studies 1 and 2 served as a first reflective exercise for many participants. Only upon detailed reflection on their projects, prompted by the interviewer, did participants realize the frequency and spectrum of their own prototype use. This finding aligns with research on the value of reflective practice to inform design behaviors and conceptions of design practices (Adams, Turns, & Atman, 2003; Schön, 1984; Valkenburg, 2009).

5.2.9 Cultural reflection

Ethical conduct is paramount in research as it influences the collection of data that forms the basis for analysis. It becomes even more important when reaching across cultures where power dynamics might differ and even the perception of what is ethical may vary (Marshall & Batten, 2004). In the studies presented in this dissertation, a white male conducted all of the interviews with a variety of participants from different geographical and socio-economic backgrounds. All questions focused on the use and impression of prototypes rather than the stakeholders themselves. However, it is still possible that some participants might have felt uncomfortable, or at least not as free to speak as they might have if another person would have conducted the interviews.

Specifically in studies 2 and 3 that were conducted in Ghana, it is possible that the presence of a foreign, white male in a local African community might have introduced a response bias on the part of the participants. This could have led to students not sharing their true thoughts in fear of consequences that might influence their course grades, or answers by medical professionals that were affirmative or not overly critical because they trusted in a concept developed by engineers outside of Ghana. One way to overcome these potential biases might be to enter a community as a member rather than an outsider (Brayda & Boyce, 2014; Marshall & Batten, 2004). This is often challenging and sometimes even impossible for researchers to personally do, but several options exist to potentially remedy this issue. For example, the research team could design the study and then hire and train a member of the local community, here an engineering student or a medical practitioner, to conduct the interviews. This could potentially result in richer feedback because of less inhibited conversations. To address other potential instances of power imbalance, cross-cultural, multi-gender research teams might be assembled to conduct interviews (Sands, Bourjolly, & Roer-Strier, 2007).

The potential for answer bias has been a concern for our study team from the beginning, but we decided to move forward for a number of reasons: First, the communities we entered in the capital of Ghana were already used to interacting with researchers from the United States. The University of Michigan has had a 30-year relationship with the Medical School at the University of Ghana (Anderson et al., 2014), including training, internships and collaborations, and the engineering programs at both universities have collaborated for close to 10 years (Ploss et al., 2017). Additionally, all participants were informed of the nature of the studies and the role of the interviewer, who himself was a student at the time of the interviews and did not personally invent the device that was used in study 3. It is still possible that some answers were biased because of a perceived power imbalance, and some answers suggested just that. For example: "If you do it right then it will work," might suggest that the reviewer was not overly critical of the device and instead trusted the design team. However, responses like "Sometimes we didn't work and made music during our group meetings" indicates that some participants were comfortable enough to speak freely and share candid information about their experiences.

5.3 Limitations and future work

One limitation of this work was the primarily focus on qualitative research. However, this approach was chosen because qualitative research aims to, and is well suited to generate deep understanding and rich description that can facilitate transferability. Our findings describe trends that might be transferable to other contexts.

Additionally, the studies presented in this dissertation relied on the experiences and information provided by participants, both novice designers and stakeholders, and interviewing was the only data collection method used across all studies. Future research might include direct observations, experiments, surveys and other methods to collect and analyze data.

Another limitation was that the participants in studies 1 and 2 self-selected and came from the same or similar educational programs. Future studies might include random selection of participants, and include participants from different programs and contexts.

Stakeholders in study 3 were limited to a unique contextual background, and the concept introduced to these stakeholders was a single medical device. Future work might broaden stakeholder background and context and introduce prototypes of different product categories.

The prototyping best practice framework was based on textbooks commonly used in engineering design. Future work could be expanded and be informed by research articles on the subject as well as interviews with industry experts. The framework could also be used to explore how industry experts follow prototyping best practice to help inform educational strategies. Future interviews could include questions that investigate the degree to which participants engaged in the prototyping best practices the “right way.” To do this, a definition of what it means to engage in each particular prototyping behavior the “right way” is necessary to complement our rating rubric for intentionality.

The research team might have introduced cultural influences to the interviews and a multi-cultural research team that includes not only local, but also peers of the participants, could conduct future interviews.

Motivating future work, we found that novice designers underutilized prototypes, in particular to engage with stakeholders, an activity that is essential for collecting input and feedback. However, an increase in stakeholder engagement alone might not be enough and instead should be accompanied by a concept called “provotyping.” Often, it is the unexpected discoveries that turn out to be essential for successful design. Instead of leaving these discoveries to chance, designers can use prototypes to "provoke" stakeholders, challenge their beliefs and "push the envelope.” In fact, some designers and researchers use the bold concept of “provotyping” or “provocative prototyping” to do just that: deliberately challenge stakeholder conceptions in design. Born in the systems design arena more than 20 years ago, provotyping has been used as a tool to reveal and challenge intellectual values and beliefs, rather than to ask practical questions (Boer & Donovan, 2012; Boer, Donovan, & Buur, 2013; Mogensen, n.d.). If conventional questions and prototypes are used to engage stakeholders to find out what they think of a proposed solution, provotypes can be used to find out how far is too far. For example, working on a new cell phone concept, a designer using conventional prototypes might ask “Which of these keyboard layouts would you prefer,” while a designer using provotypes might ask “What if you could make a phone call without a physical device?”

Prototypes often have a fairly narrow focus and are frequently used to test and verify a concept. Through the onset of “design thinking,” the focus has been widened and prototypes are now often used to communicate with and elicit information from stakeholders and users. This is and has been common practice in industrial and other design disciplines, in which prototypes have long been used broadly and to uncover user needs and wants. In many creative disciplines such as fine art and writing, artifacts like paintings, movies or stories often go further than uncovering values to deliberately challenge them. By going perhaps "too far," boundaries are discovered. In this way, provotypes can help designers and stakeholders gain insights that might otherwise be hard to identify or articulate in part because participants might not have considered such possibilities (Boer et al., 2013).

By provocation, we are not only referring to challenging stakeholder values but also prompting emotions, including positive emotions, as well as sparking inspiration or new perspectives (Kelly & Wensveen, 2014). In future work we would like to identify stakeholder boundaries, emotions and beliefs and help both stakeholders and designers better understand the solution space for a given project that ultimately leads to better design solutions.

5.4 Contributions, implications and recommendations

This research investigated how novice designers used prototypes across the design process, in different contexts as well as how intentional they were in their use of prototypes. We developed a prototyping best practice framework that included 15 prototyping behaviors and evaluated the reported behaviors with three criteria that included little to no evidence, some evidence, and evidence of intentional use. We found that novice designers often underutilized prototypes and that their behaviors frequently lacked intentionality. Next we looked at how prototypes influenced stakeholder feedback and found that prototype type, stakeholder group and question type all had an effect on stakeholder feedback. Since we have shown that stakeholder feedback is sensitive to prototype type, stakeholder group, and question type, and given that novice designers' prototype usage lacked intentionally, and that they underutilized prototypes, specifically with stakeholders, our findings point to potential missed opportunities that might impact engineering education as well as professional practice.

5.4.1 Implications for education

The participants in studies 1 and 2 were not true beginners; the experiences they reported were taken from senior capstone design courses that built upon prior design experiences. For many, this capstone course represented their final curricular design experience prior to entering professional practice. However, while our findings do not necessarily suggest misconceptions, they indicate that participants did not yet fully conceptualize the value and broad uses of prototypes. Without the opportunity to reflect, they might have done the same thing again, and reflective practice could offer a first opportunity for novice designers to be explicit in their motivation for using prototypes, and eventually arrive at more intentional and deliberate prototyping behaviors.

To facilitate a transformation to intentional practitioner, educators might increase the use of prototypes during design, but simply repeating a behavior does not make one an expert. Instead, the explicitness of reflective practice leads to intentionality and the educational setting should offer an opportunity for students to engage in reflective practice that supports this transformation. Since our findings suggest effect through analysis, educators from fields such as engineering design, design education, industrial design, design science and design research methods, as well as practitioners in professional settings might apply the same explicitness and reflective practice to develop intentional prototyping strategies including with stakeholders during design.

And while it might be challenging to ask novice designers to engage more with stakeholders and create additional prototypes that support such interactions in addition to the often already crowded curricula, these interactions might actually save designers time and several institutions have established courses and programs that include front-end design activities that encourage students to develop an understanding for stakeholder needs and wants, often in contexts different from their own (Carnegie-Mellon Design, 2017; Georgia Tech, 2017; "Global Health Design," 2018; Stanford d.school, 2017; The New School, 2017; University of Michigan, 2016, 2017).

Although the findings of this work focused on engineering capstone design students in the United States and Ghana as well as stakeholders in Ghana, the effects we saw indicate that these findings might be immediately transferable to other contexts. In addition, the prototyping best practice framework could be adopted by educators to suggest and evaluate student prototyping strategies, and by practitioners to inform their own prototyping strategies for design projects.

Ultimately, this work might help to improve pedagogical methods to teach design, including K-12 through higher education and professional practice. Our findings can inform strategies for educators to help novices to transition to designer expert through repeated, intentional and deliberate use of prototypes and reflective practice. This is important because a structured approach for when and how to use prototypes, as well as selecting prototype format, interview questions, and stakeholder groups can influence design outcomes. Our findings suggest that the commonly recommended "quick and simple" best practice for using prototypes might not always work. Instead, a context specific prototyping strategy that complements the "quick and simple" approach might be more effective.

5.4.2 Implications for professional practice

Our work has shown that stakeholder feedback is sensitive to prototype type, and ideally, designers would make informed prototyping decisions when engaging with stakeholders. However, budget and time constraints might not allow for prototypes to be created specifically to engage with stakeholders, and instead, designers might use whatever they have. This could include various types of prototypes, which has the potential to further distort stakeholder feedback by displaying some ideas in more favorable ways than others.

Additionally, it might be challenging to influence who the stakeholders are as well as to understand their experiences and background prior to collecting feedback. Ideally, designers would determine whom they will engage with and develop an understanding for what prototype type is most suitable for this audience. Therefore, the factor that might most easily be influenced and optimized is question type. Designers could remedy a not ideal stakeholder-prototype pairing by asking questions that allow stakeholders to respond, even if the context is challenging. Instead of asking general questions, designers should include in-depth explanations of product context as well as explicitly framing questions to address specific details. This should also include several prototypes of similar type and quality that allow for comparison of features, which has been shown to improve conversations around prototypes (Sarvestani & Sienko, 2014). Designers should prepare a catalog of questions designed to elicit the same information, but asked from a different perspective, and should also consider questions they might not necessarily ask but that a stakeholder might be well positioned to answer. A more exploratory approach to interviewing stakeholders might be more challenging for designers, but could lead to insight that might otherwise not have been obtained (Brayda & Boyce, 2014; Sands et al., 2007; USAID, 1996; Weiss, 1995). The question goal should be to empower stakeholders to feel like they can contribute and should avoid creating a situation that might feel overwhelming or "out of their wheelhouse."

5.4.3 List of publications

5.4.3.1 Journal publications

Deininger, M., Daly, S. R., Sienko, K. H., Lee, J. C., & Effah Kaufmann, E. (in preparation). Investigating Ghanaian novice designers' use of prototypes during design. *The International Journal of Design*

Deininger, M., Sienko, K. H., Daly, S. R., Lee, J. C., & Seifert, C. M. (under review). Prototyping for context: exploring stakeholder feedback based on prototype type, stakeholder group and question type. *Research in Engineering Design*

Deininger, M., Daly, S. R., Sienko, K. H., & Lee, J. C. (2017). Novice designers' use of prototypes in engineering design. *Design Studies*., DOI 10.1016/j.destud.2017.04.002.

5.4.3.2 Conference publications

Deininger, M., Sienko, K. H., Daly, S. R., Lee, J.C., Obed, S., & Effah Kaufmann, E. Does prototype format influence stakeholder design input? 21st International Conference on Engineering Design (ICED 2017), Vancouver, Canada, 21-25 August 2017.

Deininger, M., Daly, S. R., Sienko, K. H., & Lee, J. C., The use of prototypes by Ghanaian novice designers. Clive L. Dym Mudd Design Workshop MDW X: "Design and the future of the engineer of 2020", Harvey Mudd College, 1-3 June 2017.

Deininger, M., Sienko, K. H., Daly, S. R., Lee, J.C., & Effah Kaufmann, E. Influence Of Prototype Type On Stakeholder Engagement, 3rd WHO Global Forum on Medical Devices, Geneva, Switzerland, 10-12 May 2017.

Deininger, M., Sienko, K. H., Daly, S. R., Lee, J.C., Obed, S., & Effah Kaufmann, E. Prototyping Best Practices By Ghanaian Novice Designers, 3rd WHO Global Forum on Medical Devices, Geneva, Switzerland, 10-12 May 2017.

Deininger, M., Sienko, K. H., Daly, S. R., Lee, J.C., Obed, S., & Effah Kaufmann, E. The Use of Prototypes by Novice Designers, UM-ISL, 1 May 2017.

Deininger, M., Sienko, K. H., Daly, S. R., & Lee, J. C. Student use of prototypes to engage stakeholders during design. 123rd ASEE Annual Conference and Exposition, New Orleans, June 26-29, 2016.

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