Pursuing Inclusive Engineering Design: Centering People, Exploring Diverse Perspectives, and Promoting Divergent Thinking

by

Laura Murphy

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Design Science)
in the University of Michigan
2023

Doctoral Committee:

Professor Shanna R. Daly Co-Chair
Professor Colleen M. Seifert, Co-Chair
Professor Eytan Adar
Professor Petra Kuppers

Laura R. Murphy

lrmurphy@umich.edu

ORCID iD: 0000-0001-9476-6004

Acknowledgements

The work presented in this dissertation would not have been possible on my own. I would like to thank my wonderful community of peers and friends who have offered continual support throughout graduate school. The incredible minds of my friends in the Design Science program and beyond have continually shaped and improved both my work and myself. I am similarly indebted to my incredible therapist of many years. I am grateful to Design Science program chairs Nigel Melville and Kathleen Sienko for their mentorship, candor, and kindness. Members of the Daly Lab have offered continual support and constructive critique over the years. The faculty, lecturers, professionals, and students I have met at engineering design conferences over the years have been great sources of inspiration and guidance.

I am grateful to my committee for their engagement and support of my work over the years. In particular, I want to thank Shanna Daly for inviting me to the world of design process research and always supporting both my personal and professional goals. I appreciate Colleen Seifert for grounding our work in her extensive knowledge of cognitive science. Many thanks to Eytan Adar for offering time, mentorship, and kindness through very challenging times. I am grateful to Petra Kuppers for warmly welcoming me to her research coven, allowing me to further expand and ground my work in disability justice and engage with scholars across disciplines.

I am grateful to the ongoing support of my family. My parents among many things provided the time and space for my animals and me to take a writing retreat to complete this dissertation. I am grateful for my siblings and my lovely nieces and nephew who sparked a lot of joy for me the last few years – Eleanor, Genevieve, Frannie, Hudson, and Jane. Lots of love to my wonderful cousins, aunts, and uncles who have supported me over recent years.

The research reported in this publication was supported by the National Science Foundation (NSF) division of Engineering Education and Centers (EEC) in the CAREER program, grant #1943805, and the University of Michigan M-Cubed grant U064092 awarded to Seifert, Daly, Adar, and Brueckner. These awards and the Rackham professional development and travel grants have supported my travels to the annual conference of the American Society of Engineering Education, the International Design Engineering and Technical Conferences, and the Mudd Design Workshop.

Lastly, this dissertation would not have been possible without the unconditional love and care of my beautiful little animals – Mia, Rosie, Penelope, and Charlie.

Table of Contents

List of Tables

List of Figures

Abstract

Exploring diverse perspectives is essential in building a more inclusive world. In engineering design, this ‘exploration’ takes place through divergent thinking processes, defined as exploring a problem with many diverse perspectives and alternatives considered en route to achieving a solution. The exploration of multiple alternatives, perspectives, and people can occur in every stage of the problem-solving process, including problem definition, research, concept generation, solution approaches, methodologies, and solutions. This dissertation investigates the importance of divergent thinking in engineering to center people, explore diverse perspectives, and ultimately, advance greater inclusiveness in engineering design.

Historically, research on divergent thinking in engineering has focused on concept generation by promoting consideration of many diverse solutions to a problem, but divergent thinking can play a role in other stages of engineering work. Divergent thinking at every stage of engineering processes raises opportunities to explore alternative understanding of problems, approaches, and solutions. In practice, engineers often struggle with divergent thinking because their professional training, education, and culture focus on convergence as a dominant thinking process. The emphasis during training is the search for an “optimal,” correct solution, narrowing perspectives and limiting exploration of alternatives. Available research on the practice of divergent thinking across engineering design is limited, suggesting the need for further scaffolding to support engineers in exploring diverse approaches and perspectives.

In this dissertation, my collection of studies investigates divergent thinking in engineering in multiple ways. First, I examine how students’ divergent thinking about people changes through explicitly representing people when generating concepts. Qualitative and experimental studies assess the impact of an explicit request to depict people in sketches when generating early concept designs. Next, I examined the ways practitioners explored (or failed to explore) diverse perspectives during engineering projects. A qualitative study with a diverse group of engineering practitioners examines their personal experiences divergently exploring stakeholders during engineering projects. My qualitative analysis defines individual, interpersonal, and organizational barriers and facilitators to divergent thinking in engineering. Finally, I examine practitioner experiences through a larger qualitative study across stages of engineering projects to identify broader dimensions influencing engineers' ability to implement divergent thinking during engineering projects in the field.

The results of my studies offer actionable strategies and dimensions of practice that support engineers as they employ divergent thinking. In lab studies with design students, adding representations of people in concept sketches resulted in deeper exploration of users' contexts and interactions with designs. My analysis of practitioners' divergent thinking about stakeholders identified ways individuals and organizations may prevent or facilitate the exploration of diverse perspectives during an engineering project. My broader analysis of practitioner experiences with divergent thinking across the stages of engineering processes outlines potential changes to promote divergent approaches and avoid limitations from convergence dominance in engineering culture. These studies provide guidance for engineers on how to incorporate divergent thinking in their projects and highlight how divergent thinking in engineering is shaped by structures and processes in engineering organizations. My dissertation contributes explicit recommendations to better support divergent thinking across engineering processes as a tool for centering people, exploring diverse perspectives, and ultimately advancing inclusive engineering design.

Chapter 1 Background, Overview, and Motivation

1.1 Introduction and Background

Engaging diverse perspectives is key in advancing inclusive engineering outcomes. Divergent thinking, the process of exploring many diverse options and perspectives, can be a way for engineers to explore and value diverse perspectives across all engineering activities. Divergent thinking is about thinking flexibly and creatively, honoring that there are many potential ways to approach and solve problems, that diverse perspectives offer unique and important insights, and that no single person is going to have all the answers. Divergent thinking can be useful across engineering, such as when generating potential solutions to a problem, identifying relevant stakeholders, or exploring problem-solving approaches.

Divergent thinking about people is particularly relevant for supporting inclusive engineering design. Over the last several decades, engineering educators and practitioners have focused increasingly on centering people in engineering design. “Centering” people during design includes divergently exploring the ways people are impacted by design decisions. These human-centered practices emerged as a way to better solve increasingly complex engineering challenges. As an example, in 2022 the University of Michigan’s College of Engineering introduced a campaign for “people-first engineering” in response to extensive research on the future needs of engineering education (Michigan Engineering, 2023). Further, leading engineering organizations such as the American Society for Engineering Education and IEEE emphasize service to humanity and inclusion of diverse stakeholders as key parts of their visions (Adams & Fortenberry, n.d.; IEEE, 2019).

Centering people and diverse perspectives in design helps engineers better understand the context in which designs will be used, the needs of the target communities, and the various potential implications of design decisions. When we break engineering design down to its core activities, how are we supporting engineers in centering people and diverse perspectives at each of those problem-solving stages? This dissertation investigates divergent thinking as a tool for centering people, exploring diverse perspectives, and ultimately advancing inclusive engineering design.

1.1.1 Defining engineering design

Engineering processes broadly involve the activities engineers take to develop solutions to problems. One name for that problem-solving process is design, where engineers move through various design 'stages.' Atman and colleagues (2007) describe three stages of engineering design: 1) problem scoping: identification of a need, problem definition, and gathering information; 2) developing alternative solutions: generating ideas, modeling, feasibility analysis, evaluation; and 3) project realization: decisions, communication, and implementation (Atman et al., 2007).

In this dissertation, I define all engineering work through the lens of design. Not all engineers identify their work as design; similarly, literature on problem solving from psychology does not use the name 'design.' Yet, any process by which someone solves a problem where there is not one right answer means they are *designing* a solution. Design is naturally divergent and open-ended, meaning there is multiplicity in problems, approaches, and solutions; in contrast, "problem-solving" perhaps gives the impression that there is a single problem that has a single solution. The difference in language is part of the problem in engineering – divergence is a key part of understanding and solving complex problems, yet engineering processes tend to emphasize convergence. While the language to describe engineering problem-solving may differ across fields, in this dissertation I use the term *engineering design* to describe the process of engineers understanding a need, determining problem-solving approaches, developing potential solutions, and implementing those solutions.

1.1.2 Divergent thinking and its benefits

Divergent thinking is the process of exploring many diverse options and perspectives (Brophy, 2001; Runco, 1999). It emerged primarily in cognitive psychology research that identified the connection between divergent thinking and creativity (Runco, 2010). Divergent thinking was originally studied as an indicator of creativity, known to be an important part of successful design processes (D. Cropley, 2016). Divergent thinking is an aspect of creativity and has been shown to contribute to it (Ma, 2009; Runco, 2010); further, divergent thinking can indicate designers' ability to generate original ideas and creatively solve problems (Runco, 2023). Unlike other measures of creativity like novelty, usefulness, or originality (Sarkar & Chakrabarti, 2007; Shah, Smith, & Vargas-Hernandez, 2003), divergence is a *way of thinking* that can shift the way engineers approach complex problems. Divergent thinking is especially important in the early stages of a design process, often called *front-end design* in engineering, when design decisions have important impacts on the ultimate success of design outcomes (Khurana & Rosenthal, 1998). Improving divergent thinking in the front-end is therefore especially important to improving design outcomes. Existing research on divergent thinking has primarily focused on conceptual design, yet divergent thinking can be useful beyond conceptual design activities.

Divergent thinking affords many benefits to engineers. Divergence and creativity are both key to solving complex engineering problems (D. Cropley, 2016). One meta-analysis of studies on creativity showed that divergent thinking is key to creativity (Ma, 2009). Research has shown that training students across disciplines to think divergently helped them to think more flexibly and improved problem-solving (Scott et al., 2004; van de Kamp et al., 2015). In those studies, one investigated divergent thinking broadly as the ability to generate diverse responses to open-ended problems (van de Kamp et al., 2015), while the other investigated divergent thinking more narrowly as the ability to generate many alternative solutions (Scott et al., 2004). One study demonstrated that people who were more successful practicing divergent thinking were more successful entrepreneurs (Ames & Runco, 2005). The 'entrepreneur' participants were nominated by their local chamber of commerce for having started at least one business, so they were not necessarily trained as engineers. Another study found that expert inventors were most successful at deliberately controlling the use of divergent thinking during complex problem solving (Wolf & Mieg, 2010). That study identified 'inventors' as professionals with at least one patent, meaning the participants were again not necessarily trained as engineers. One further limitation of that study is that the patent-granting process is not necessarily representative of all great innovation, as patents require many resources to achieve and maintain. More work is needed to describe the practice and effect of divergent thinking on engineering professionals.

Some scholars describe certain divergent thinking attributes like being curious, experimenting, and taking risks as a key part of interdisciplinary work (McAuliffe, 2016). Being able to engage across disciplines is essential for engineers (National Academy of Engineering, 2004; Ruth, 2018), yet poses many challenges for both education and practice. One review of interdisciplinary engineering education found many challenges in teaching interdisciplinary skills in higher education, such as the "siloed nature" of academia and the need for more scaffolding strategies (Van den Beemt et al., 2020). Divergent thinking practices may support more engagement with interdisciplinary work within both engineering education and practice.

1.1.3 Challenges in practicing divergent thinking

Thinking divergently is challenging for many engineers. Research has repeatedly shown that engineers tend to struggle with design fixation, or inability to move beyond initial ideas (Cross, 2001; Jansson & Smith, 1991). A study of design professionals identified that 'fixation' takes places not only with design concepts, but also with problem understanding and the processes or approaches designers consider to solve problems (Crilly, 2015). This attachment to initial ideas and approaches can be damaging to conceptual design outcomes. One study demonstrated that participants' initial generated concepts were most likely to already have been suggested by other participants (Kudrowitz & Dippo, 2013), suggesting that diverging beyond initial ideas is an important way to generate more innovative outcomes.

One way that divergent thinking can be challenging for engineers is engineers' difficulty with 'metacognition,' or awareness of one's own thought processes (Marzano et al., 1988). While metacognition can be useful across many contexts, multiple scholars describe divergent thinking as requiring metacognition. Metacognition can be challenging for engineering students and practitioners, in part because it is not emphasized in engineering curriculum (Davis et al., 2013). A study of engineering students' metacognition found that students often misjudge the complexity of a task, lack confidence in their ability to meet expectations on a project, or lack the time, resources, and support to evaluate their progress (Lawanto, 2010). One study on divergent thinking training described metacognition as a key part of teaching divergent thinking to students (van de Kamp et al., 2015). A different study found that metacognition was key in experts leveraging both divergent and convergent thinking skills (Wolf & Mieg, 2010).

Metacognition can be tied to reflective practices, as recommended for more effective professional practice (Schön, 1983).

Very little pedagogy exists to help engineers to think divergently beyond the concept generation stage, in part because engineering education predominantly focuses on convergent analytical skills (Felder, 1988; Valentine et al., 2019). One study of engineering courses found almost no evidence of teaching divergent thinking skills, instead finding content focusing on convergent skills like analysis and evaluation (Daly et al., 2014). A study of 1,100 electrical engineering courses found less than 2% of courses had an explicit focus on creativity (Valentine et al., 2019), underlining a need for further research on pedagogical strategies to support divergence. One meta-analysis of creativity training emphasized that students significantly improved their divergent thinking practices when provided with appropriate guidance (Scott et al., 2004). This finding encourages efforts to further develop pedagogical strategies and scaffolding to support divergent thinking.

1.1.4 Opportunities for divergent thinking

One of the biggest areas of research for divergent thinking in engineering design is concept generation, the process of generating many diverse potential solutions to a problem (Cross, 2008; Osborn, 1957). This makes sense as concept generation is a key engineering design activity (Dym & Little, 2004) and is also seen to be an effective measure of divergent thinking (Hyun Lee & Ostwald, 2022; Runco, 2010). Many strategies exist to support engineers in divergently exploring many potential solutions to a problem, such as Brainstorming (Osborn, 1957), Design Heuristics (Daly et al., 2012; Yilmaz et al., 2016), or Morphological Analysis (Allen, 1962). Research has described the impact of these various strategies and their implementation. For example, Daly and colleagues compared engineering students' use of those three particular strategies and found Design Heuristics and Morphological Analysis led to more elaboration of concepts; they also found Design Heuristics produced more practical concepts and that all three strategies produced about the same diversity of solution sets (Daly et al., 2016). I previously led a study to examine further differences in Brainstorming and Design Heuristics, identifying that the latter supported exploration of individual components of a system, led to more unusual ideas, and helped students question key assumptions embedded in solutions (Murphy, Daly, et al., 2022). Similarly, parallel (as opposed to serial) prototyping has been shown to help designers explore more divergent potential solutions to a problem rather than fixating on a single solution type (Dow et al., 2010).

Engineers benefit from diverging when exploring their understanding of a design problem. Literature demonstrates the problem exploration is key to ensure designers are solving the *right* problem (Volkema, 1983). This practice of reframing problems is useful not only in the problem-solving process of design, but is also important in navigating communication with project clients (Paton & Dorst, 2011). One strategy for problem exploration is to expand the scope of the problem to expand potential solutions (Volkema, 1983). Another strategy to explore a problem is a process called 'solution mapping' where designers test many, divergent assumptions to learn if their solution could solve yet unidentified problems (Lee et al., 2021). Questioning and exploring a provided problem can be challenging for engineers, especially in a context where the individual has little power or support to expand or reframe the scope of a project (Wedell-Wedellsborg, 2017).

Engineers might seek to diverge in the ways they approach solving problems. Flexibility of approach has been shown to be important in solving design problems (Cross, 2001). One study found that novice designers fixated on a single activity to solve problems (trial and error) while experienced designers would explore and combine multiple activities depending on the problem context (Ahmed et al., 2003). Similarly, Ball and Ormerod (1995) described that expert designers leverage flexibility in their problem-solving approaches, shifting between a “breadth-first” or a “depth-first” solution development depending on the context and project constraints.

When ‘gathering information,’ engineers can seek out many diverse sources of information to inform their background contextual research. One study found that designers relied heavily on interpersonal exchanges to support development of innovative ideas (Salter & Gann, 2003). Other work identified that difference sources of information impacted designers’ empathy towards potential users (van Rijn et al., 2011). They described that direct contact with users most positively influenced product quality and empathy outcomes. They also found that intrinsic factors of designers like willingness and motivation affected designers’ ability to empathize with users.

1.1.5 Exploration of diverse perspectives

One part of practicing divergent thinking is exploring diverse perspectives. Engaging stakeholders is a key part of engineering design (Dym & Little, 2004), and exploring a diverse set of stakeholders is a key element of producing inclusive designs (Costanza-Chock, 2020; Shum et al., 2016). Current literature describes some ways that engineers diverge to explore diverse perspectives. One study found that engineers may explore problems by taking multiple perspectives, gaining new understandings through varied lenses (Murray et al., 2019). For example, one strategy identified in that study involved identifying various subgroups within a primary stakeholder group. Another study described expanding the primary stakeholder group in order to expand the scope of the problem (Studer et al., 2018).

Stakeholder exploration can take place across various stages of engineering design. Some scholars describe stakeholder exploration as a part of developing understanding of a problem, arguing that engineers can more organically identify relevant stakeholders as they come to understand the broader system in which the project exists (Salado & Nilchiani, 2013). Others emphasize stakeholder exploration during later stages of analysis and design (Berlin et al., 2021). More recent work has expanded on ways to engage stakeholders across engineering design by leveraging various forms of prototypes (Deininger et al., 2019; Rodriguez-Calero et al., 2020).

Exploring diverse perspectives can be challenging for designers. Research has shown that designers limit or even stop engaging with stakeholders when their perspectives do not align with one another (Gambo et al., 2022; Niles et al., 2020; van Lamsweerde et al., 1998). A study on engineering students found that students struggled in many ways when engaging in complex, divergent, and sometime ambiguous public welfare issues (Niles et al., 2020). Participatory design practices suggest long-term engagement with diverse communities to advance 'sustainable social change' (Smith & Iversen, 2018), but most literature on exploring and identifying stakeholders exists in business management literature. In fact, one extensive of stakeholder exploration methods in particular established the need for further research to understand and recommend best practices (Pacheco & Garcia, 2012). While not directly studying engineering design, a related study summarized that most ergonomics and human factors research does not report leveraging any structured method to explore stakeholders (Berlin et al., 2021). The documented struggles and lack of processes emphasize the need for further scaffolding to support designers in exploring diverse perspectives.

Exploring diverse perspectives is a key aspect of 'people-centered' design processes, such as human-centered design (IDEO, 2015; D. Norman, 2013), user-centered design (Norman

& Draper, 1986), inclusive design (Inclusive Design Research Centre, n.d.; Shum et al., 2016), ability-based design (Wobbrock et al., 2011), participatory design (Sanders, 2002; Smith & Iversen, 2018), and design justice (Costanza-Chock, 2020; Design Justice Network, 2018), to name a few. These varying design approaches provide a lens through which designers select, prioritize, and approach various design activities, all with the aim of closing the gap between people's needs and design outcomes. The approaches emphasize different values, often examining power dynamics and other social factors that influence how designers execute their work. For example, design justice encourages designers to center the voices of the community in which the design will be implemented (Design Justice Network, 2018). Thus, design justice emphasizes not only engaging with communities, but empowering (and resourcing) communities with ownership over design decisions (Costanza-Chock, 2020). One of those people-centered approaches is inclusive design, which is the primary motivation of this dissertation. My work centers inclusive design as a means of expanding and improving the ways engineering design processes diverge to consider people across design activities.

1.2 Motivation

1.2.1 Positionality

My motivation for the work presented in this dissertation is rooted in a desire to shift the processes by which the world is designed to more inclusive practices. I propose to do this by helping engineers to explore and center the experiences of diverse stakeholders to inform engineering decisions.

I identify as a white cisgender woman. These identities have influenced my educational and professional experiences as an engineer. While being a woman in engineering has been extremely challenging, my other identities have afforded me many privileges. I have been able to enter the predominantly cisgender white spaces that make up the engineering community with relative safety and build a broad network of engineering and academic professionals. I worked as a professional design engineer for four years before coming to graduate school. I experienced first-hand the challenges engineers face in accounting for diverse perspectives; I observed engineers failing to consider the implications of their decisions on a variety of stakeholders; I saw engineering organizations failing to provide the time and resources to engage deeply with diverse stakeholders. These experiences influenced my decision to study the experiences of practicing engineers to inform the work of this dissertation.

My professional background is, in part, engineering product design for people with physical disabilities. I spent years learning directly from disabled people about their lived experiences in the built world, and once I started graduate school I dove into literature written by disabled scholars to further build that knowledge. It was not immediately obvious what the connection between this passion for disability justice and engineering design process research was going to be, but I felt so inspired and guided by the wealth of knowledge in the written words of disabled people, scholars or otherwise. As a designer, it was impossible to read about or witness the lived experiences of disabled people and *not* see the lessons to be learned and applied in design. In these ways, the wisdom of disabled experiences have consistently shaped and informed the study design, analysis, and interpretations presented in this dissertation.

1.2.1.1 Academic lineage

In my committee member Petra Kuppers' most recent book *Eco Soma*, she began with a list of her "citable" or "archive-explorable" lineage (Kuppers, 2021). Following that example, I do the same to honor the minds that have predominantly shaped my working thoughts over the past several years. This academic lineage is certainly one-sided; I do not imply that any of those from whom I have found wisdom and guidance endorse my work.

In 2020, disabled activist and writer Alice Wong edited and published an anthology of first-person stories from 37 different disabled people (Wong, 2020). The stories represent the variety, richness, joy, and challenges of living with disabilities. As an engineer and designer, one cannot read these stories without understanding the ways the designed world fails disabled people. The stories echo the many years of work and hundreds of people with disabilities I personally interviewed to better understand their experiences. I am grateful for this tangible and accessible record of disabled experiences.

I am indebted to the work of many scholars in disability studies fields, including Aimi Hamraie, Sara Hendren, Alison Kafer, Rosemarie Garland Thomson, Simi Linton, Elizabeth Guffey, Bess Williamson, and Leah Lakshmi Piepzna-Samarasinha. Other forms of knowledge have been equally as valuable to me: online I have learned countless lessons on disability justice from Imani Barbarin, Emily Ladau, Vilissa Thompson, Kate Speer, and Haben Girma. These creators and others have generated incredible campaigns such as #AcademicAbleism, #SayDisabled, #DisabilityTooWhite, and #ThingsDisabledPeopleKnow. Stephanie Masta's work, among many things, has taught me that adoption of ideas is much bigger than individual arguments and the dissemination of knowledge. Daniela Rosner, Cynthia Bennett, and Erin Cech have beautiful centered disability and ableism within engineering design literature. I am also indebted to the many wonderful scholars I have met at the American Society of Engineering Education and International Design Engineering and Technical conferences over the last several years who have encouraged and shaped my work.

1.2.2 Inclusive design

Divergent thinking practices support consideration of diverse perspectives, a core tenet of inclusive design. The last decade of my academic and professional practice has been rooted in inclusive design; as such, I provide an introduction to inclusive design which broadly motivates the research questions and analysis choices made through this dissertation.

Inclusive design centers the lived experiences of people with disabilities as an intersectional way of addressing many design inequities. Inclusive design is an approach that developed from the experiences of disabled people encountering barriers in the designed world. Many people-centered design approaches seek to answer the question: how do we more fully consider people during design? Inclusive design additionally questions: who do we consider during design? Inclusive design prioritizes recognizing exclusion, learning from diversity, and the process of 'solve for one, extend to many' (Shum et al., 2016). Accounting for a wide variety of people helps engineers identify what are known in disability studies as "openings" (Wendell, 1996), "misfits" (Garland-Thomson, 2011), or "mismatches" (Holmes, 2018). These mismatches are opportunities for engineering solutions to create harmony between people and the built world. Engineering design often focuses on achieving technical functions, but design can go beyond meeting basic needs; design can elevate people's experience in the world (Hendren, 2020).

Given that inclusive design has its roots in disabled experiences, it is important to understand how varying definitions of disability relate to engineering design work. These definitions are not mutually exclusive - any or all of these definitions can be at play in any given moment. The dominant understanding of disability in engineering is a medical framing, a belief that people have conditions that must be cured or solved so those people can fall back within the realm of 'normal.' If the conditions are incurable, a medical framing asserts that we must provide disabled people with assistive technology (e.g. prosthetics, wheelchairs, screen readers) so they can function in 'normal' society (Linton, 1998). The medical definition centers disability on the individual: there is a fault in the individual person that needs to be changed in order to fit in.

My work centers disability as socially constructed, meaning that no one person is disabled; rather, the world we have built is disabling to some people and enabling to others (Oliver, 2013). A basic example of the social construction of disability is ramps: people who use wheelchairs are disabled by stairs, but enabled by ramps. The people themselves have not changed, but their built environment is either disabling or enabling. There is also undoubtedly a social identity claimed by disabled people that influences their sense of self and community connection (Linton, 1998). Disability may be situational, temporary, or permanent, as articulated by the nuance in Shum and colleagues suggested 'persona spectrum,' a more dynamic way of representing peoples' varying abilities (Shum et al., 2016). Finally, an aspect of disability that transcends all definitions is the experience of pain that often accompanies living with a disability (Bendelow & Williams, 1995). The reality of pain as a circumstance that may not be 'solvable' lies in contrast to many fundamental beliefs of engineering problem solving, but is an important perspective of disability to reckon with.

The rich nature of disabled experiences lay the groundwork for inclusion across many other dimensions of ways people are different from one another – transness, queerness, race, gender identity, citizenship, etc. Disability crosses every realm of human variation and can impact anyone at any time. Wendell articulates the particular and vibrant untapped knowledge that comes from disabled people and disabled communities: "Collectively, we [disabled people] have accumulated a significant body of knowledge, with a different standpoint (or standpoints) from those without disabilities, and that knowledge, which has been ignored or repressed in nondisabled culture, should be further developed and articulated" (Wendell, 1996). The current reality of 'developing and articulating' disabled experiences within engineering is largely a problematic one, emphasizing the need to apply inclusive design principles with care.

Disability within engineering is predominately understood within a medical framing, meaning disability is something to be cured or solved. While many engineering innovations to support disabled people's independence are important, often disability-related engineering projects center nondisabled perspectives. Linton articulates: "It is often startling to nondisabled people that many disabled people do not pine for nondisabled experience" (Linton, 1998). A classic example of nondisabled perspective applied in engineering are the many attempts at stair-climbing wheelchairs. Videos of stair-climbing wheelchairs regularly garner millions of views online, yet if one eventually comes to fruition it will likely be wildly expensive and inaccessible. Disabled author Emily Ladau responded to one particular stair-climbing wheelchair design on Twitter: "Idea for tech students who design stair-climbing wheelchairs: invent a power wheelchair with a back-up battery to alleviate anxiety that comes with getting stuck due to a dead battery. Maybe solar-operated? And call it the Solar Roller ™. That would actually be world-changing" (Ladau, 2019). Her comments remind me of the ways engineering design could be incredibly useful to disabled people, yet it continues to fall short of people's real needs.

Another problematic view of disability within engineering is that disabled needs require special accommodations or custom design. Engineers often reference a bell curve or designing for statistical averages, otherwise understood as 'normal' people. This practice developed predominantly in ergonomics or industrial design for military applications tracing back to the World Wars (Singleton, 1971). The practice of designing for the average has reached far beyond military design and has become a commonplace and harmful practice across engineering and design work. Engineering professor Sara Hendren describes how this obsession with 'normal' is socially constructed: "When the average is laden with cultural worth, everything changes: what was common began to be seen as what was "natural," and what was "natural" became to be seen as right" (Garland-Thomson, 2017; Hendren, 2020). Engineers are capable of successfully accounting for some ranges of human variation; for example, many different body types can comfortably fit into the seat of a car. The decision to account for some types of human variation but not other types is a political and social one.

I identify these examples not because my work explicitly studies disabled people, but because each study's research questions and methodologies were informed by inclusive design principles. To understand how we might ethically and effectively apply inclusive design principles to engineering design, it is essential to understand the current reckoning of disability in engineering spaces. My work seeks to center the lessons there are to learn from disabled experiences within engineering work, both to improve design for disabled people and to improve design for all people.

1.2.3 Why it is important to center people in engineering: A short story

As a second year undergraduate in a mechanical engineering program, I enrolled in a mandatory solid mechanics course. Solid mechanics is a core mechanical engineering competency – it introduces engineers to mathematically evaluate the basic structures that make up the built world. While the coursework primarily presented problems on paper in the form of, "X beam has Y force placed on it in Z direction," my instructor was known for taking the work off the paper and grounding us in real-world examples. He would contextualize each of the main concepts with real-world structures, typically ones with prominent engineering failures. We learned of the infamous Silver Bridge collapse during rush-hour traffic (West Virginia Department of Transportation, 2022); we watched black-and-white videos of the 1940 Tacoma Narrows Bridge oscillating like a concrete wave (Smithsonian National Air and Space Museum, 2019); we drew diagrams of the ceiling rod design that led to the Hyatt Regency walkway collapse (Hernandez, 2021).

Those stories stuck with me nearly a decade later because they were striking and devastating and real. I thought I knew the stories well. And yet, a few years back I came across a podcast that told those stories from the *human* perspective rather than the technical engineering one. Those stories painted the picture of how many hours and days it took to recover all the survivors and bodies of the walkway collapse, the long-term trauma that wore on emergency responders, and the lasting community impact of such a devastating event. I listened in shock as these stories, so mechanically familiar to me, revealed how little I knew about the impact these engineering failures had on people.

I knew the physical justification and devastation of the engineering failure, but looking back I realized we had not once talked about the people impacted. The way we discussed the engineering failures now seems so cold, devoid of compassion for the human impact of engineering decisions. It is emblematic of the ways that core engineering culture seem to find ways to silo our humanity from our engineering work, when in fact our own and others' humanity is central to just, equitable, and inclusive engineering outcomes.

This experience and many others have motivated the primary question of this dissertation: When we break engineering design down to its core activities, how are we supporting engineers in centering people and diverse perspectives at each of those problem-solving stages?

1.3 Chapter Overviews

This dissertation follows a three-paper model, where Chapters 2, 3, and 4 have been submitted as independent publications. As such, the research team contributing to each chapter varies, as is noted at the beginning of each chapter. While I wrote the introduction and discussion chapters from my perspective ("I"), the study chapters represent the actions of the respective research teams ("we") defined in each chapter.

Chapter 2 investigates the concept generation processes of undergraduate design students to understand how to promote divergent exploration of users and their interactions with designs through centering people. I present a series of in-lab concept generation studies testing an intervention that asks students to include representations of "people, a person, or parts of a person" in their conceptual sketches. I sought to understand how students represent people within design concepts, and how that representation influences their thinking during concept generation. Student sketches, recorded think-aloud protocol, and post-task reflections reveal multiple ways that with the intervention students more divergently explored the people impacted by their designs.

Chapters 3 and 4 present analysis of 20 interviews with engineering practitioners about their experiences with divergent thinking. In Chapter 3, I look closely at how practitioners talk about their experiences (and challenges) with exploring a diverse group of stakeholders. Leveraging multiple rounds of qualitative inductive coding, I identified various reasons why practitioners find value in exploring stakeholders. Additionally, I identified several barriers and facilitators to divergent exploration of stakeholders. These barriers and facilitators provide insights to practitioners, educators, and engineering organizations on how to better support engagement with diverse perspectives.

In Chapter 4, I examined the practitioner interview data across stages in the engineering process to identify what facilitates or inhibits practitioners' ability to think divergently. The dimensions practitioners cited as supporting or inhibiting divergent thinking highlight the ways that both individuals and organizations shape the way divergent thinking takes place in practice. Further, this chapter examines the limitations arising from the convergent norms of engineering culture for engineering problem-solving.

Across all three studies, I leveraged a variety of qualitative methods to collect and analyze data. Qualitative methods allow for deep, rich, and nuanced understanding of student and practitioner experiences. In Chapter 2, I collected data in the form of student sketches, written descriptions, and think-aloud protocol. In Chapters 3 and 4, I collected data through semi-structured interviews which allowed for both consistency across practitioners and opportunities to probe for additional depth in practitioner experiences. To analyze data, I leveraged multiple rounds of thematic analysis, inductive coding, and contextually appropriate statistics to demonstrate significance of findings. These methods allowed themes to emerge from participant data rather than imposing preconceived notions; additionally, these methods accounted for the positionality of the researchers.

The strategies and dimensions of practice identified help to illuminate the many challenges engineers face in exploring diverse perspectives, but also offer divergent thinking as a tool for advancing inclusive engineering design. The work outlined in this dissertation contributes to the growing body of knowledge about how engineers can build a more just, inclusive world.

Chapter 2 Where are the Humans in Human-Centered Design? Representing People during Concept Generation

This chapter investigates the impact of an intervention on student designers' divergent exploration of the people impacted by designed solutions, guided by the framing question: How do designers use divergent thinking to explore end users during early concept design? The work presented in this chapter was conducted by myself, Thanina Makhlouf, Shanna R. Daly, Eytan Adar, and Colleen M. Seifert, with contributions to the first experiment design from Dr. Sophia Brueckner.

2.1 Introduction

Over the last several decades, designers have increasingly emphasized human-centered design processes to better meet peoples' complex needs. "Centering" people during design includes divergently exploring the ways people are impacted by design decisions, often during key design activities like problem definition and scoping, prototyping, concept generation, and evaluation (Atman et al., 2007; Dym & Little, 2004). The "people" of interest to human-centered designers include anyone who could impact or be impacted by designed solutions. Often called stakeholders (Freeman, 2010), these people might include project managers, product manufacturers, policymakers, or community members, but perhaps the most important stakeholder is the primary end user of a designed solution.

One opportunity to center end users is during concept generation, the process of exploring many potential solutions to a problem through sketching and describing multiple ideas

(Cross, 2008; S. R. Daly et al., 2016a; Khurana & Rosenthal, 1998). Concept generation often occurs independently, for example when following best practices for Brainstorming where designers generate concepts on their own first before coming together as a team (Osborn, 1963; Wilson, 2006). One way designers center people and their needs during concept generation is through a design approach called co-design, where designers invite potential users to jointly develop potential solutions to a problem (Sanders & Stappers, 2008). Co-design is perhaps the gold standard of user engagement and exploration, but co-design approaches are not always possible. Thus, designers may often generate concepts on their own or with their team when it is still important for designers to be thinking about people. As an early stage design activity, concept generation can have important impacts on the ultimate success of design outcomes (Khurana & Rosenthal, 1998), and therefore could be a key opportunity for incorporating user perspectives.

Beyond co-design, limited strategies have been offered to support designers in centering users during the concept generation stage. In a novel approach, Dahl and colleagues posited that designers are not consistently imagining the end user during concept design (Dahl et al., 2001). Their study asked undergraduate engineering students to design a concept by imagining either existing or potential designs, with some further directed to imagine "an elderly person being involved with and interacting with the proposed product design." Instructions to incorporate a "customer" within an imagined design resulted in more appealing and useful concepts. Imagining end users interacting with a potential design may bound exploration by focusing attention on people.

But which people? How is their interaction with a design considered? And, what desirable qualities of designs are identified through this process? To address these questions, we explored how design students imagined people during the concept generation process in two studies. In a first qualitative study, a think-aloud protocol captured more information about *how* designers thought about people while generating concepts. In a single session with one design problem, undergraduate student designers first generated concepts on their own and then repeated the task with instructions to represent "people, a person, or part of a person" within each of their sketches. This simple instruction may encourage considering how people will interact with a design without limiting who students can consider or requiring training on how to imagine interaction. A second experimental study with engineering design students directly compared the impact of representing people in concept sketches on exploring users to a control.

Our research goals were to identify how student designers considered people during concept generation, and whether their design thinking changed when they included people within their concept sketches. If successful, representing people in designs may be a simple intervention to promote exploring multiple perspectives of end-users during concept generation, leading to successful design through more divergent thinking about people.

2.2 Background

A main purpose of design is to develop solutions to people's problems, but as technology advances and our understanding of the complexity of people's lives deepens, identifying and implementing contextually appropriate designs becomes more difficult. Designers have a responsibility to adjust their design processes to attend to that complexity. One of the biggest shifts in design processes to arise from these complex and so-called "wicked" problems (Buchanan, 1992) is a closer focus on *people* throughout a design process. Professionals and researchers across design fields have sought people-focused approaches to create designs that more closely meet human needs.

A variety of people-focused design approaches specify differing methods to center people as key players in developing designs, such as human-centered design, design thinking, ergonomics, human-computer interaction, user-centered design, and inclusive design. While today these design approaches are often conflated and overlap in many ways, they each developed in distinct disciplines and therefore offer different values, perspectives, and practices. All of these people-focused design approaches seek to close the gap between human needs and design outcomes, seeking to understand users' needs and their contexts holistically (Zhang & Dong, 2009; Zoltowski et al., 2012). Many approaches focus on considering the 'person' who will become the primary end user, while others define people impacted by design more broadly to account for a variety of stakeholders beyond the end user.

2.2.1 Design approaches for centering people

Human-centered design has been primarily developed in product design spaces with a focus on engaging a variety of stakeholders in early-stage design activities (IDEO, 2015, 2019; D. Norman, 2013). Ergonomics developed primarily from design for military applications and helps designers account for users' physical bodies (Singleton, 1971). Human-computer interaction emerged from work across computer science and cognitive science and focuses on how users might interface with digital technology (Carroll, 1997). Inclusive design grew from experiences of disabled people within a product design context and prioritizes who is excluded and included by design decisions (Hendren, 2020; Inclusive Design Research Centre, n.d.; Shum et al., 2016). User-centered design developed in a product design and engineering context and focuses on product experience and usability (D. A. Norman & Draper, 1986). Ability-based design developed in computer science and engineering and emphasizes designing for users' varying *abilities* instead of designing for *disability* (Wobbrock et al., 2011). Sanders (2006) described design research along a spectrum of users seen as subjects to users seen as partners (Sanders, 2006).

A key emphasis across these design approaches is the role of empathy (Hess & Fila, 2016; IDEO, 2019; Kramer et al., 2016). Empathy is necessary to understand people's experiences and incorporate their perspectives into design decisions. To be effective, empathy requires more than knowing about the user. Rather, the designer has to relate to the user and understand their feelings, experiences, and perspectives (Kouprie & Visser, 2009). Brown (2021) describes empathy as "the most powerful tool of compassion." She writes, "Rather than walking in your shoes, I need to learn how to listen to the story you tell about what it's like in your shoes and believe you even when it doesn't match my experiences" (Brown, 2021). Bennett and Rosner (2019) further state that rather than perceiving empathy as an end goal in design, designers should understand empathy as a "creative process of reciprocation" (Bennett & Rosner, 2019).

2.2.2 Methods for centering people

One way to center and empathize with users during design is to engage directly with them. For example, practitioners leverage multiple different strategies during early-stage design activities, like problem definition and initial prototyping, to engage deeply with users (e.g. IDEO, 2015; Rodriguez-Calero et al., 2020). Similarly, there are many strategies to engage users directly in later-stage design activities, such as usability testing (Dumas & Redish, 1999). Ozcelik and colleagues (2011) found that industry practitioners focus mainly on what users *say* through tools like interviews and surveys, what users *do* through tools like shadowing or usability testing, and, least often, what users *make* through collaborative generation sessions. A form of user engagement throughout concept generation is called co-creation or co-design, where designers and users work together to generate solution ideas (Sanders & Stappers, 2008).

There are also times in design work where designers may not engage directly with their users, but still seek to center them in design activities. Designers might translate identified user needs into requirements or specifications to meet during later design stages (Dieter & Schmidt, 2012; Dym & Little, 2004; Nuseibeh & Easterbrook, 2000). Another strategy is storyboards which are visual representations of what a user experience might be while engaging with a designed solution (Corrie, 2006). Designers might represent users in the form of personas, a visual profile developed from aggregated user data that can serve as inspiration and guidance for designers (Miaskiewicz & Kozar, 2011). Some designers leverage empathy-building simulation or role-playing to gain the experience of users (Alzheimer's Association, 2018; Bearman et al., 2015). The empathy-building success of each strategy may vary; for example, many sources criticize the morality and effectiveness of simulation and role-playing (Bennett & Rosner, 2019; Kafer, 2013; Siebers, 2008). Temporarily simulating a disability such as blindness or using a wheelchair for a day does not acknowledge the nuanced skills people develop over time (Bennett & Rosner, 2019) nor does it acknowledge the cultural, structural, and social aspects of disability (Linton, 1998; Oliver, 2013). One meta-analysis of disability simulation found no positive effects and several negative effects (Flower et al., 2007). Ozcelik and colleagues (2011) identified many cultural and logistical barriers to engaging users in design processes, including that practitioners lacked strategies to collect user information and effectively implement it (Ozcelik et al., 2011).

When working on designs independently, deep empathy for users can be challenging. A limited number of tools exist to support considering users during concept generation. Design

Heuristics, a set of 77 strategies to help designers generate more diverse ideas, include some user-specific prompts such as: "*Allow user to customize*" and "*Attach product to user*" (Yilmaz et al., 2016). The 'human-centeredness' of these particular prompts has not been studied, though they do not appear to offer a holistic perspective of people. One study investigated artificial intelligence (AI) prompts that replace human input as a way to mimic co-creation (Karimi et al., 2020), which introduces many ethical concerns given the complex outcomes of applying AI across other contexts (e.g. Turner Lee et al., 2019). Despite the desire and need for designers to keep people in mind during design, methods to support designers in centering people currently fall short.

2.2.3 Centering people through mental visualization

Dahl and colleagues (2001) proposed mental visualization as a method for centering people during concept generation. In their studies, engineering students worked alone in a single session to generate one potential solution to a design problem ("a car jack for seniors"). To encourage thinking about the "customer" during design, students were told, "*...many designers find that using imagination to form visual images (pictures in the mind) of potential designs can help them to produce innovative and effective designs,*" and some received an added training exercise using a guided visualization procedure. In addition, some students were directed to imagine "an elderly person being involved with and interacting with the proposed product design."

The results showed that most designers on their own are not consistently imagining the end user during concept design. When students later described their images, the control group (with no instructions given) averaged just 0.6 images including a customer. Even when instructed to imagine designs, students did not include many people within their mental images, averaging 0.59 customer images. However, when prompted to imagine customers *interacting* with their potential design, customer images doubled to an average of 1.5, and combined with guided visualization training, increased to an average of 2.69 customer images. A second experiment found designs where visualizations of customers were reported were rated as both more appealing and useful.

Instructions to imagine end users *interacting* with a potential design may increase exploration of solutions focused on people. These results suggest an innovative intervention to aid designers in centering people during concept generation, but pose several limitations to implement in a design process. First, the somewhat lengthy and challenging two-part instructions are to 1) visualize potential designs and 2) incorporate customers interacting with them. In addition, the design task in the study was to generate a single design solution, but best practices recommend generating multiple designs – as many as possible – to explore alternative solutions. This instruction limits the impact of imagining users to a single design, but considering user interactions may spur related ideas and multiple visualizations. The only visualization evidence during the design process came from reports by students after completing their design. Contemporaneous evidence in the concept sketches generated during the task may better support conclusions about impact on design processes.

Another potential concern is the introduction of a specified "target customer" for the design (a senior, 20 to 24-year-old women). These descriptions may be necessary for some design problems, but they may suggest specific ways to consider possible users and discourage broader exploration. For example, designers are unlikely to consider whether age is even relevant to the design when it is presented to them as part of problem. An open-ended prompt may allow considering a more diverse range of people, how users may differ from each other, and alternative stakeholders in the design (for example, driver, passenger, caregiver, mechanic). Further, the findings do not reveal the people imagined, how they interacted with the designs, or what desirable qualities for design were identified by designers through this process.

To address these questions, our first study explored how undergraduate students in mechanical engineering design, user experience design, and art and design programs imagined people during the concept generation process. More encouragement is needed to promote divergent thinking about people, so we asked student designers in a single session to create multiple concepts for a design problem and to sketch and describe each concept as they worked. Rather than a complex, two-stage intervention on imagining and considering people interacting with concepts, we offered a simple instruction to depict people within concept sketches. This positions the consideration of people during concept design to occur as the concept is committed to paper during sketching. The need to place a person within the concept sketch implicitly raises the question of their relationship to the design, promoting the desired processes of visualization and imagining potential users.

We employed a think-aloud protocol to capture more information about the ways designers think about people while generating concepts. To compare "natural" processes when considering people to a planned intervention, students first generated concepts on their own and then repeated the design task with instructions to represent "people, a person, or part of a person" within each of their sketches. This simple instruction may encourage considering how people will interact with a candidate design without specifying *who* to consider or receiving training on *how* to imagine interaction (as in Dahl et al., 2001). The within-subject AB design allows us to ask the designers themselves about any changes in their thinking following the intervention. A second study uses experimental methods between subjects to draw conclusions about the effectiveness of the intervention.

The central question for the project was: How do designers use divergent thinking to explore end users during early concept design? Our research goals in two studies were to identify how student designers consider people during early concept generation, and whether their design thinking changes when people are included within their concept sketches. The simple instruction to represent people within concept sketches may be an effective method to support designers' consideration of end-users when generating concepts, leading to more diverse design solutions.

2.3 Study 1: How Do Student Designs and Thinking Change When Drawing People?

2.3.1 Method

Our research study investigated representations of people in conceptual sketches and consideration of potential users by design students during concept generation. The following research questions guided the study:

1) How do students represent people within design concepts, and how does that representation influence their concept generation?
2) How are students' concepts and thinking impacted when they are specifically asked to include people or parts of a person within their sketches?

To answer the first question, we analyzed how students represented people before and after being prompted to do so. We addressed the second question through analyses of think-aloud protocols and inductive analysis of patterns across concepts. To detect differences before and after asking students to include people in their sketches, we used a within-subjects study design where each participant generated concepts for a single design problem before and after the intervention.

This single-case AB design is effective in testing the impact of an intervention. In this study, the familiar condition (natural concept generation) occurred first and the intervention (including representations of people) occurred second for all students.

2.3.1.1 Research team positionality

Drs. Daly, Adar, Seifert, and Brueckner, and I collaborated on preliminary experimental design, pulling from expertise across our varying fields (mechanical engineering, human-computer interaction, cognitive science, and art and design). The interdisciplinary group of scholars influenced the student participants we chose to study, the design problem we created for the experiments, and the holistic view with which we approached studying ways to support centering humans during design. Dr. Daly, Dr. Seifert, and I had previously conducted studies of concept generation (e.g., Murphy, Daly, et al., 2022), which supported the choice to study concept generation and informed the experimental designs. I conducted all in-person data collection, and Makhlouf and I together collaborated on data analysis with regular input from Drs. Daly and Seifert.

2.3.1.2 Participants

Participants for the study included 15 fourth-year undergraduate university students in 3 design-based disciplines: 5 mechanical engineering students, 5 art and design students, and 5 user experience design students. Nine students reported their gender as female, five as male, and one did not indicate. Students identified their race and/or ethnicity as Indian American (1), Asian American (2), white (3), Hispanic (1), Latina (1), Latine (1), Indian (1), and Asian (3), and multi-racial (2). Students were recruited through email lists in their respective schools of study. Students received $25 as compensation.

2.3.1.3 Procedure

Each participant engaged individually in a single one-hour session including pre-intervention and post-intervention concept generation. The study followed a “think aloud” protocol where the participants spoke aloud to describe their thinking as they generated concepts for the given problem, as described in Atman and Bursic’s description of verbal protocol analysis (Atman & Bursic, 1998). Before beginning the concept generation, participants practiced the think aloud protocol using a brief problem to verify that they understood the protocol, as recommended by Ericsson and Simon (Ericsson & Simon, 1980). Throughout the study, when a participant stopped talking aloud, the facilitator prompted them by saying, “Please keep talking.”

For the pre-intervention concept generation session, we instructed participants to generate as many concepts as possible to solve the provided design problem (Figure 1). We asked participants to create a sketch and written description for each concept. We provided participants with concept generation worksheets on which to document their concepts. The facilitator instructed participants to include any information they wanted in their concept sketches and enough details and written descriptions for each concept to be able to be understood just by looking at it.

We provided a design problem to participants as a context to generate solution concepts. The research team developed the design problem to be easily understood by undergraduate students of different backgrounds and experiences while affording a wide range of possible solutions. Figure 1 shows the design problem prompt provided to participants.

Design Problem: Helping people move

Moving is considered one of the top stressors in life. When people move, they experience multiple challenges. For example:

- lifting heavy furniture
- navigating through small spaces (door frames, corners, narrow hallways, stairs)
- keeping belongings organized
- finding other people to help them move
- continuing living (and even working) while belongings are in transit
- moving in extreme weather (snow, heat, rain)
- and many others…

Imagine you are asked to design for this problem. Considering one or more challenges on movingng day, design a way to *help people move households.* Make sure to consider the physical setting in your solution.

Figure 1: Design problem provided to students

After 15 minutes, the first concept generation task ended and we introduced the intervention in verbal instructions. Participants were instructed to represent "people, a person, or part of a person" within their sketches during a second 15-minute concept generation task. We used this specific language to allow participants the freedom to draw a single person or multiple people, or to draw a full body image or part of a body, such as showing a close-up image of hand operating a phone application. Thus, the representations of people could be flexible across any concept the participants wished to generate. We provided participants with five example illustrations showing people within concept sketches, shown in Figure 2. With these new instructions, we asked participants to generate as many concepts as possible for the same design problem for another 15 minutes. The study lasted about 60 minutes in total.

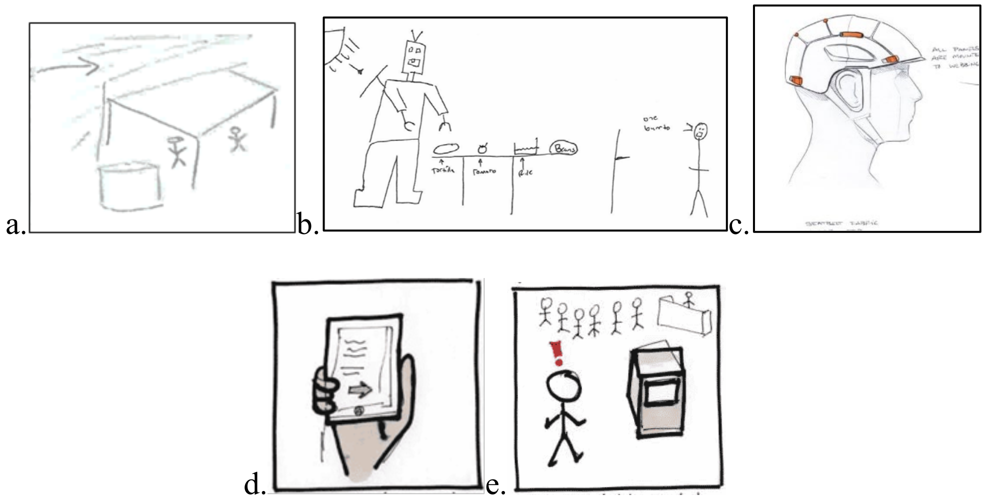


Figure 2: Five example sketches including representations of people provided to participants in the intervention (image C sourced from Laut Design (2023); images D and E sources with permission from Trucchia (2020))

2.3.1.4 Data Analysis

I. Analysis of sketches

For each concept, we considered its concept worksheet with sketch and written concept description and a transcript of the think-aloud protocol during that portion of the concept generation task. Two example concepts from different participants are shown in Figure 3.

We began by examining each participant's set of designs to compare their sketches made before and after the intervention. First, we scored each sketch for the presence of a depiction of a person or body part. The sketch quality was in general quite basic, with "stick" figures often used to indicate a person. Then, we developed a coding scheme for how people were depicted through an iterative process following thematic patterns identified while examining the data (Creswell, 2013). The five independent themes (shown in Table 1) address qualities shown in sketches representing people, including emotion, communication, physical interaction, full body depictions, and multiple people. Each theme was then coded dichotomously for each sketch.

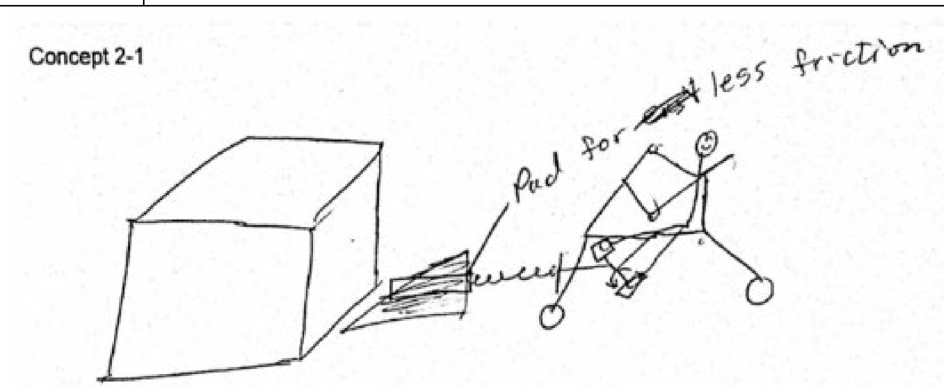
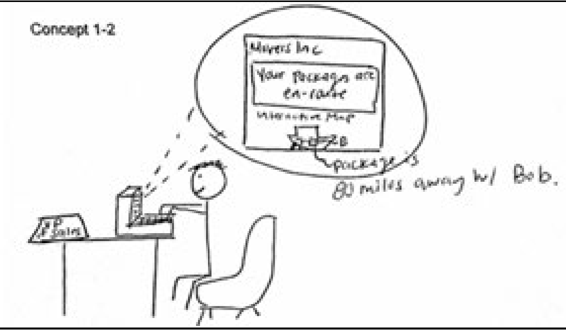
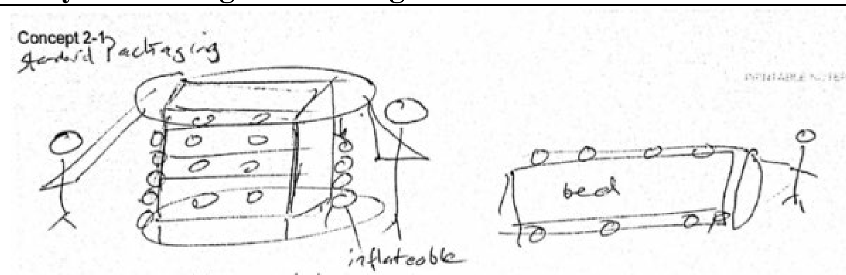
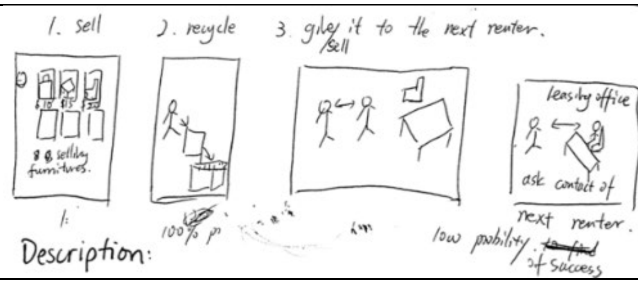
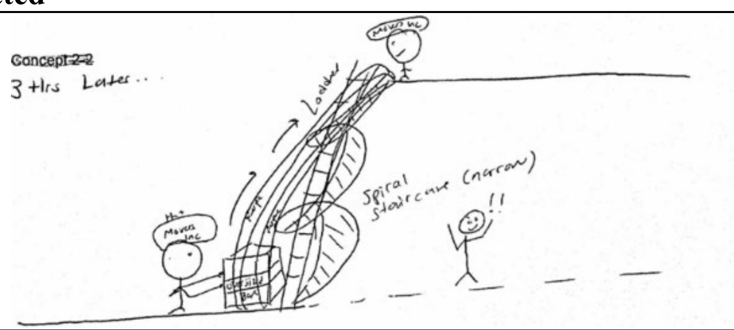
<table>
<tr><td colspan="2"></td></tr>
<tr><td>Participant’s Written Concept Description:
1. App/online organize resources and requires
2. Robot/Machine</td><td>Think-Aloud Transcription: “The user requirement can be finding other people to help them to move. So I think first, maybe an app to clearly... No, to organize resources, such as moving companies, and the users who want some people to help them to move. An app, or some simply online website, or tools, that help people to move.”</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Participant’s Written Concept Description: Bike style pedals to push slider under heavy objects and move objects around</td><td>Think-Aloud Transcription: So the first one I would say, I still want to focus on is lifting heavy furniture or lifting heavy boxes. So I might say... Bicycle. You would get...Let's say you have a heavy box and... You need something to lift it up. So you just have like a wedge. Oh, this is not really well drawn. Oh well. A wedge. And there's a crank or a screw of some sort, and it's powered by this chair that has a bicycle. And there is a person, his feet on that bicycle. And as they peddle, it pushes the wedge under the box and... or it pushes the pad under the box. Pad for easy pushing or for less friction. So the pad gets pushed under the box, and then once the pad is under the box, they can just move... or the stop will hit the box and then they can essentially just bicycle their way over... that's how you draw a bicycle. So, it's actually this pad goes under the box. So, bike-style pedals to push slider under heavy objects and move objects around. It works. Somehow the steering gets figured out and let that happened.</td></tr>
</table>

Figure 3: Examples of concepts from two participants, including sketch, written description, and think-aloud transcript during concept generation tasks

Table 1: Definitions of thematic codes capturing representations of people in participants' sketches

<table>
<tr><td colspan="2">Sketch explicitly depicts emotion</td></tr>
<tr><td>Example: Smiling at message</td><td>
</td></tr>
<tr><td colspan="2">Depicted person is physically interacting with a design</td></tr>
<tr><td>Example: People stacking materials</td><td>
</td></tr>
<tr><td colspan="2">Depicts a person's full body</td></tr>
<tr><td>Example: Alternative removal steps</td><td>
</td></tr>
<tr><td colspan="2">More than one person is depicted</td></tr>
<tr><td>Example: Second floor moves</td><td>
</td></tr>
<tr><td colspan="2">Communication between people is displayed</td></tr>
<tr><td>Example: Posting on web page</td><td>
</td></tr>
</table>

All sketches were coded by Makhlouf and I, and discrepancies were discussed to consensus (Landis & Koch, 1977). Table 2 shows the percent agreement and Cohen's *kappa* for each category, indicating satisfactory agreement (Cohen, 1960).

Table 2: Agreement and inter-rater reliability for categorization of person representations in sketches

Representation Category:	**Displays human emotion**	**Person interacts physically**	**Depicts a person's full body**	**Depicts more than one person**	**Displays interpersonal communication**
Percent Agreement	100%	88.2%	94.1%	88.2%	87.9%
Cohen's kappa	1.000 – perfect agreement	0.534 – moderate agreement	0.765 – substantial agreement	0.768 – substantial agreement	0.602 – moderate agreement

II. Analysis of descriptions in think-aloud protocols

Through the think-aloud protocols, we sought to understand the different ways participants thought about people while designing. We expected references to "the user" (e.g., the person moving), but participants additionally referred to the intended user's family, friends, and companies helping them. Makhlouf and I independently considered the sets of think-aloud protocols before and after the intervention to identify how participants spoke about people. Through multiple rounds of discussion, the larger research team argued to consensus that there were four categories of differing references to people: a general level ("everyone"), a type of person, a specific individual, and the designer themselves (as "me" or "I") (see Table 3). Coding examined the section of think-aloud transcripts associated with each individual concept and categorized them based on the generality of references. This measure was not influenced by the *number of times* a reference occurred, but by the number of *different* reference categories observed for each concept. For example, a complete transcript for one concept might include both general and self-references. Participants sometimes changed their level of generality while discussing a single concept.

Table 3: Reference categories capturing the level of generality in references to people while generating concepts

Terms Refer to:	**Definition**	**Examples**
General	Intended for 'everyone,' no specific type or actual person identified. *Examples:* "everyone," "people," "person," "we," "they," "he/she/they," and the generic "you"	"The *user* requirement can be finding *other people* to help *them* to move." "Say there are a few boxes, and after *you* moved to a new place, *you'll* know which thing's in which box."
Types of People	Refers to subgroups of people with certain qualifications or contexts. *Examples:* "tall people" or "people with a big family;" hypotheticals and societal roles, e.g., "renter" and "homeowner."	"So I have to talk with the guy, with the leasing office to ask contact of *next renter* if they have one." "I will draw a muscular person with little bulges on the arms to show that *he's a mover*."
Specific Individuals	References to particular, real individuals. *Examples:* "my brother" or "this friend of mine."	"So I've *younger sister*, but she's a lot stronger than I am. There's been many a time where *my dad* has asked us to help him move a table or something."
The Self	Self-references from personal experiences or as users. (No references to designer role were counted; e.g., "Now I'm going to focus on other people...")	"*I* wouldn't want my boxes getting stuck in the rain or anything especially while *I was moving, I* wouldn't want anything to get wet. "

Makhlouf and I categorized all references by concept in the think-aloud transcripts using these four categories, and discussed any discrepancies to consensus. Table 4 shows the percent agreement and Cohen's *kappa* for each category, with satisfactory agreement for each.

Table 4: Agreement and inter-rater reliability for categorization of reference generality

Category:	**Everyone**	**Type of Person**	**Specific Individuals**	**Self**
Percent Agreement	100%	92.1%	97.2%	91.7%
Cohen's kappa	1 – perfect agreement	0.821 – almost perfect agreement	N/A – too few occurrences to calculate	0.719 – substantial agreement

III. Analysis of Changes between Pre- and Post-Intervention Sessions

Makhlouf and I collaborated on identifying qualitative changes, if any, in how participants talked about people in the think-aloud protocols between the first and second tasks for each participant. I noted and recorded changes over the sessions while conducting the study. Then, Makhlouf and I independently compared think-aloud protocols before and after the intervention for each student, focusing on descriptions of people. We leveraged memoing (Charmaz, 2006) to record changes and noted differentiating characteristics. We included participants' identifications of stakeholders, aspects of stakeholder context, and interactions between stakeholders and design solutions. Through discussions with the broader research team, six different patterns were described, with three occurring in multiple protocols. These observed thematic changes following intervention capture qualitative changes in how participants addressed people within their concept designs.

2.3.2 Results

The 15 participants – five mechanical engineering, five art and design, and five user experience design – produced 106 concepts over the two concept generation sessions. The mean number of concepts generated across both concept generation tasks was 7.1 (SD=3.1), with a range from 4 to 14 (see Table 5). In the first task, 30% (n = 17) of concepts were scored as depicting a person, and in the second task, 90% (n = 46) did so, indicating participants successfully followed the instructions of the intervention.

Table 5: Number of concepts generated pre- and post-intervention, and number of concepts depicting people by each participant

Concepts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total	Avg (SD)
Pre-IV Total	4	4	8	2	2	2	3	4	5	6	3	2	3	6	2	56	3.7 (1.8)
Pre-IV with People	1	0	3	0	0	1	0	1	3	0	3	0	1	4	0	17	1.1 (1.4)
Post IV Total	7	3	6	2	3	2	2	2	4	4	2	2	4	4	3	50	3.3 (1.5)
Post IV with People	7	3	6	2	3	2	2	2	4	4	1	1	4	4	1	46	3.1 (1.8)
Total	11	7	14	4	5	4	5	6	9	10	5	4	7	10	5	106	7.1 (3.1)
Total with People	8	3	9	2	3	3	2	3	7	4	4	1	5	8	1	63	4.2 (2.6)

2.3.2.1 Representations of people in sketches

Of the total 106 concept sketches, 63 (59%) included depictions of people, with the majority (46) occurring after the intervention. Figure 4 shows the distribution of sketches across five identified themes: emotion, physical interaction, full body depiction, multiple people, and communication between people.

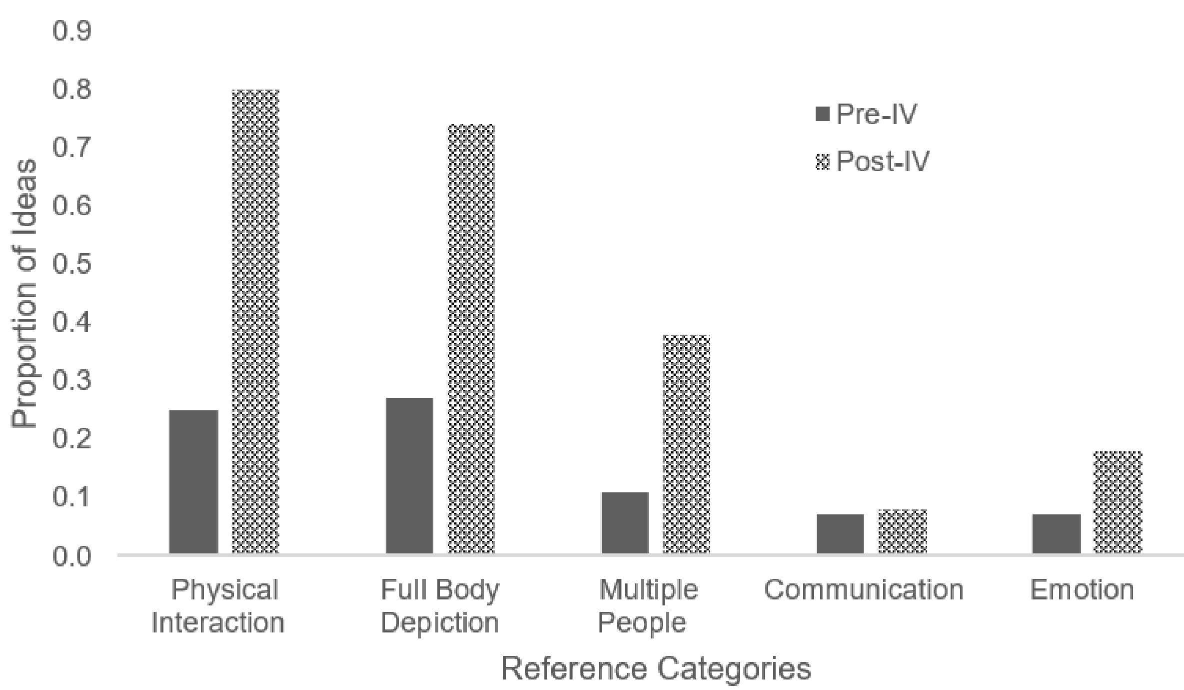


Figure 4: Distribution of sketches pre-intervention (n=56) and post-intervention (n=50) observed for five identified themes: physical interaction, full body depiction, multiple people, communication, and emotion

The number of sketches for all reference categories increased following the intervention, although depictions of communication increased very little. Across both sessions, physical interaction and full body depictions occurred most frequently. The greatest change following the intervention occurred within the physical interaction category, indicating that participants increased their consideration of how users might interact physically with their designed solutions.

2.3.2.2 Generality of references to people in think-aloud protocol

Think-aloud protocols revealed explicit references to people in almost all concept transcript segments. Only one concept -- generated before the intervention -- had no direct reference to people. References to specific individuals were very rare, while the majority of references to people across both concept generation tasks were very generic (e.g. “people,” “they,” “everyone”). The proportions of references to people across the four categories (*General, Type of Person, Individuals,* and *Self)* are shown in Table 6. The small differences observed in the generality of references to people indicate little change after the intervention.

Table 6: Similar proportions of reference categories were observed in think-aloud protocol concept segments (n=106) before and after the intervention

Reference Categories	**Example references**	**Proportion Pre-IV (n)**	**Proportion Post-IV(n)**	**Difference (n)**
General	“people,” “they”	.66 (53)	.61 (49)	.05 (4)
Type of Person	“tall people”	.18 (14)	.21 (17)	.03 (3)
Specific Individuals	“my brother”	.04 (3)	.04 (3)	.00 (0)
Self	“me,” “I”	.12 (10)	.14 (11)	.02 (1)
Total		1.00 (80)	1.00 (80)	
Total Concepts		56	50	

2.3.2.3 Qualitative changes in consideration of people before and after intervention

Most of the participants shifted their consideration of context and stakeholders based on the intervention in several ways, as represented in Table 7. There was not any single shift common across all participants, rather many distinct shifts that we describe in qualitative form in the following paragraphs (emphases in italics are added to reflect analysis).

Table 7: Description of qualitative changes in considering people following the intervention

Post-intervention shift	**Participants (n=15)**	**Description of shift in designs**
Center User	10, 12	Places users at the center of designs
Consider Emotions	3, 5	Considers user's emotional needs
Consider Physicality	2, 6	Considers physical contexts of users
Consider Community	7	Considers a community of stakeholders
Consider Others' Experiences	13	Considers others' life experiences
Consider Past Experiences	14	Focuses on own specific life experiences
None of the above	1, 4, 8, 9, 11, 15	No apparent changes

Center User. One type of shift observed was a noticeable change from not considering users to users being central to the concepts they were creating (Participants 10 and 12). Initially, these participants made almost no references to any potential users and made only general references to people: for example, "Light containers can be moved by *a person*" (Participant 12). After the intervention, they discussed people as central to each concept. For example, Participant 10 gave a detailed description of a person's interaction with each design: "And there is a person, his feet on that bicycle. And as they peddle, it pushes the wedge under the box." Participant 12 also centered users in designs by considering ways that different people might engage at various stages of the concept solution, including possible roles and actions: "If [I] give [furniture] to the next renter, I only have to talk with them and I can keep all my furniture in the house so I don't have to move them... So I have to talk with the guy, with the leasing office to ask [for the] contact of [the] next renter if they have one." Both participants changed focus to center specific circumstances people might experience following the intervention.

Consider Emotions. A different shift occurred in considering the emotional context of potential users. For example, Participant 3 addressed only the physical context of use before the intervention. After the intervention, they introduced the emotional stress a person moving might experience, and how that context may influence design decisions: “So, they're helping her take the boxes into the new house to ease heavy lifting and maybe emotional stress to have her friends there with her.” Similarly, Participant 5 addressed emotional stress and feelings of loss during a move: “I feel like that's something that people might struggle with, with just the stress of moving, there's no real way to say goodbye to a place that you lived. Maybe that's a pain point that people might have, especially if they've lived in a place for a while.” Following the intervention, these participants identified new qualities of user needs in the domain of emotional context.

Consider Physicality. Two other participants seemed to make an opposite shift after the intervention; that is, they went from considering user emotions before (Participant 2: “The emotional stresses... not being in control of the situation;" Participant 6: "emotional significance") to a focus on specific physical contexts after the intervention. Participant 2 thought through a very detailed process of how a user physically engages with their concept: “So the user will assemble this mechanism on the armchair. So they put the handle here and then they take their other hand and they put the backing inside. So, internal. And then they can use this magnet handle to change the way that they're holding the different items without damaging the items.” Participant 6 also focused on physicality: “So I guess, I'm being asked include people, a person or parts of a person *makes me think more about the physicality of things* just because that brings body parts into it. And so now I'm thinking about the physical annoyance of moving and what that would look like.” It appears the intervention acted as a reminder to consider a different area of user needs than they had previously rather than dictating a specific area of user needs to consider.

Consider Community: A different shift moved from focusing on a single person to understanding how a community of people might interact with a design. For example, Participant 7 first identified what a "generic" user (someone moving) needs: “These materials have to be lightweight because you don't want heavy boxes. And actually, holes would help because then you're using less material. So actually, I think all moving boxes really should have a decent amount of holes in them, unless they need to keep things insulated.” In contrast after the intervention, Participant 7 discussed many different people engaging with a concept, and that their motivations differ: “This is the person who wants to move…Needs help, physical help. So then that would be these people. But these people need incentive to help. Let's draw, these are drawing household items. And then their incentive, receive unwanted household items. And they also are giving away items in moving.” Following the intervention, the participant considered people beyond the target user, and how people may influence each other.

Consider Others' Experiences: For other participants, after the intervention, their concept generation shifted to considering different people’s life experiences rather than solely their own. For example, before the intervention, Participant 13’s every concept was related to their own personal experiences living in college dorms: “Okay, so I guess one problem that stands out to me from moving around dorms to apartments and things like that, would be the idea of having to pack up everything in such a short time while still living in the space and wanting to continue living there before you move into your new space.” In the second task, Participant 13 spoke hypothetically about a situation they had not personally experienced: “So he goes into the store, and maybe it's a moving store that also does this, I don't know. Part of the store is that they help you move your things, so you go into the store and you chat with this guy and he says, ‘Okay, I'll handle it for you.’ And then he talks to the mover... so, owner, mover... and tells him the situation.

So, 'tells him the situation', mover says, ‘Okay, I can do it tomorrow.’” In the first example, the potential user described is the participant himself, whereas in the second example the potential user is a different imagined person.

Consider Past Experiences: Finally, it appeared that one participant discussed people in general terms only before the intervention, and then addressed his own individual experiences more directly following it. For example, Participant 14 spoke very generically about people before the intervention: “The user requirement can be finding other people to help them to move.” After the intervention, he pulled inspiration from real experiences he had been through: “So when I first moved to [City], I spent a couple of days going to buy furnitures (sic), and take them back to my home. It's painful to move the Ikea furniture, even though they are broken to pieces, I still have to carry it from the first floor to the third.” This shift suggests the intervention encouraged this participant to reflect on real lived experiences, and to include more elements in their designs that specifically and directly address those experiences.

Six of the participants (40%) (Participants 1, 4, 8, 9, 11, and 15) showed little difference in how they discussed people before and after the intervention. For example, Participant 11 drew people in all sketches both before and after the intervention, and their protocols were equally detailed, involved, and engaged with users. Similarly, Participant 15 talked a lot about people while creating their designs both before and after the intervention. For some participants, the intervention may have been unnecessary because they already incorporated people in their thinking. However, other participants appeared unaffected by the intervention despite signs that it may be helpful to them. Participant 9 discussed people minimally before and after intervention, and expressed discomfort with sketching people following the intervention: “For lifting heavy weights, for people like me, who are freaking weak, we are going to make an arm. First, we're going to draw a person and that's believable *(sarcastic)*. We're going to do a person or something and an arm and it comes out like that." Each time Participant 9 began drawing a person, she made comments about how bad her sketch was, potentially distracting her from the aim of designing for people. Other participants also expressed concern about their ability to realistically depict a person even though sketches of physical objects were similarly inexpert.

In sum, the invention appeared to result in variable responses from participant designers. While some appeared to show little change, other participants introduced new foci (e.g., emotional vs. physical), new potential users (community), and identified new user needs and experiences to consider in their designs following an intervention suggesting they include people in their sketches.

2.3.3 Discussion

In this first study, we found the prompt for students to represent people explicitly in sketches led to changes in students' designs. Students rarely included representations of people in their sketches pre-intervention. After the intervention, all students represented people in their sketches with important improvements to their representations. After the intervention, students generated slightly fewer concepts (about 10% less). This difference may reflect a slowing of concept generation due to idea exhaustion (Gray et al., 2019) in the second task, a typical finding across repeated concept generation tasks. The intervention instructed students to represent users in their concepts as they created them, potentially requiring a change in their design processes that likely required some additional time to consider.

After the intervention, more concepts included how the users would be physically integrated with the design. Considering physical integration is critical for designs requiring direct interactions with users' bodies; for example, one study found positive impacts of practicing somaesthetic reflection during ideation, a practice where the designer mindfully brings attention to interactions between their body and the designed object (Wonjun et al., 2014). Similarly, concepts after the intervention more often included peoples' full bodies. The tendency to consider full bodies could be more or less useful to designers depending on the design context.

Inclusion of peoples' emotions in concepts occurred more often for some after the intervention. Prior research has shown that empathy involves understanding potential users' feelings and perspectives (Kouprie & Visser, 2009), so the increased focus on emotional context could indicate an increase of empathy for potential users. Further, added design elements depicting communications between people, or simply the fact that more sketches considered interactions between multiple people, may indicate that students are thinking more deeply about stakeholders' contexts. Zoltowski and colleagues noted that one way students demonstrate better understanding of their users and design context is by taking more factors and complexity into consideration (Zoltowski et al., 2012). This increased consideration of connections between people could be a sign that representing people promotes deeper thought about users' contexts.

Deeper qualitative analysis revealed multi-faceted effects of the intervention. Within the sample of fifteen students, we identified differing impacts of the intervention for nine of the students as they talked about people. The shifts made by students post-intervention included moving from rarely discussing people to integral descriptions motivating and explaining each concept after the intervention. Some of the students shifted from considering people's physical context to their emotional context, indicating deeper empathy for how emotions can impact the success of designs (Artacho et al., 2010; McDonagh et al., 2009). In contrast, other students shifted from an emotional context towards the physical context. Both physical and emotional contexts are important to consider when designing for real-life scenarios, but particular students may be more likely to consider one over the other. Further work is needed to understand whether the intervention might consistently prompt consideration of new contexts, how it might be adapted to help students move in a particular direction, and how disciplinary training may support specific directions.

The intervention spurred some students to expand their discussion of people to different types of people beyond the primary end user. While some students first focused on a single user, the intervention seemed to prompt students to consider multiple other stakeholders, such as movers, landlords, and neighbors, who might also engage with a design. The consideration of a community of people indicates greater complexity and nuance when generating concepts, suggesting an increased awareness of socially engaged design (Center for Socially Engaged Design, 2020). Further, people do not exist as completely independent; rather, we exist as part of our communities, giving and receiving care and resources (Piepzna-Samarasinha, 2018). Therefore, the attention to people beyond the primary user reflects a more accurate understanding of people's social circumstances.

Rather than speaking about people in generic terms (i.e. *'the user requirement'*), some student concepts in the second task were inspired by more complex scenarios or personal experiences. Duquenoy and Thimbleby (1999) articulated how without an intervention to the contrary, designers often design for themselves (Duquenoy & Thimbleby, 1999). Further, generic language has been shown to be a way of people extending their own experiences onto others as a way of meaning-making (Orvell et al., 2017). It is possible this movement away from generic towards specific descriptions of people indicates a move away from students designing for themselves. Many people-focused design approaches emphasize the importance of understanding the variety of potential users beyond oneself (Costanza-Chock, 2020; Shum et al., 2016). While the phenomenon requires further investigation to fully unpack, the explicit evidence that the designer was grounded in rich descriptions of their personal experiences seemed to be an improvement from the vague, generic descriptions before the intervention.

In sum, the intervention appeared successful in helping students across disciplines think differently about the people using their designs. The findings suggest that the intervention helped students to divergently explore the ways people might be impacted by a designed solution through consideration of various aspects of potential users' contexts. Representations of people are not always necessary in design, but their presence may encourage attention to specific elements of human-centered design; for example, if a sketch does not include a person, there is no visual explanation offered for how a user might physically engage with a product, potentially hindering further design development or communication. Representations of people may make it easier for designers to visualize how those concepts will become a reality for users.

2.4 Study 2: Does Drawing People Change Concept Designs?

In the first study, we employed a single-case AB design where all students participated in both concept generation tasks. While this approach revealed useful information about shifts in concept generation, we sought to examine if these differences would be consistent in a larger sample. Further, we wanted an experimental design where students did not have to engage in two concept generation sessions as we wanted to remove the potential exhaustion effect (Gray et al., 2019) of a second concept generation session. Thus, we designed a second study, guided by the same research questions as the first study, but with a larger sample and different experimental design structure.

2.4.1 Method

2.4.1.1 Participants

Participants for the study included 42 undergraduate university students studying mechanical engineering. Students ranged from their second to fourth years of undergraduate study, all of them having completed at least one project-based engineering design course. Students included 27 men, 14 women, and 1 non-binary person. Students identified as Asian (21), white (11), multi-racial (9), and Hispanic/Latinx (1). Students were recruited through email lists of a mechanical engineering department. Each student received $30 as compensation for their time in completing the study.

2.4.1.2 Materials

In order to make direct comparisons between the first and second studies presented in this chapter, we provided participants with the same design problem, "help people move households," as described in Figure 1. We provided participants with an excess of concept worksheets to record as many concept sketches and written descriptions as possible within the timeframe.

2.4.1.3 Procedure

In this experiment, the design sessions were conducted with small groups of participants in the same room. Participants performed the same individual design task as in Study 1, but worked only on paper without any talk-aloud protocol. Participants were assigned at random to sessions where they either received the intervention (n = 20) or received no intervention in a control group (n = 22). Both worked alone to generate concepts for 30 minutes with the same design problem. The facilitator instructed participants to include any information they wanted in their concept sketches and to add enough details and written descriptions for each concept for someone else to understand it. The experimental group received the additional request that they represent “people, a person, or parts of a person” in their sketches. We provided the experimental group with a printed sheet of the example illustrations of people as in the first study, shown in Figure 2.

After the concept generation session ended, we asked participants to return to each concept and respond to the questions: “Who is this idea for? Who do you imagine would use it?” Participants worked at their own pace for up to 15 minutes to complete their written responses to the questions for all their concepts.

2.4.1.4 Data analysis

For each concept, we analyzed all participants’ concept sketches. We leveraged the themes inductively identified in Study 1 to compare the sketches: emotion, communication, physical integration, multiple people vs. one person, and full body vs. partial body (described with examples in Table 1). With previously established high inter-rater reliability between two coders, a single researcher completed all coding for this study while blind to condition (experimental or control).

Further analysis focused on participants' written responses to the questions, “Who is this idea for?" and "Who do you imagine would use it?” Makhlouf and I first examined all responses in a randomized order. Then, the responses for each concept were coded into categories based on similarities in the user descriptions. The categories were generated independently by Makhlouf and I and then compared and discussed to consensus, following recommended practices of thematic analysis (Braun & Clarke, 2006; Clarke & Braun, 2013). For example, one response noted that, "This could be used by movers and everyday people. This idea is for people who live in areas with extreme weather (or just for people who chose a bad day to move).” This response was coded as referring to *people who are movers*, *people who are everyday people, people experiencing extreme weather*.

2.4.2 Results

Participants in both groups generated between 2 and 9 concepts; the control group generated an average of 4.8 concepts (SD = 1.7); participants in the experimental group generated an average of 4.5 concepts (SD = 1.6). The control group (n = 22) generated 106 concepts total; the experimental group (n = 20) generated 89 concepts total.

Of the total 195 concept sketches, 107 (54.9%) included depictions of people, and the majority of them (80) occurred in the experimental group. Figure 5 shows the distribution of the sketches across the five identified themes: emotion, physical integration, people's full body, multiple people, and communication.

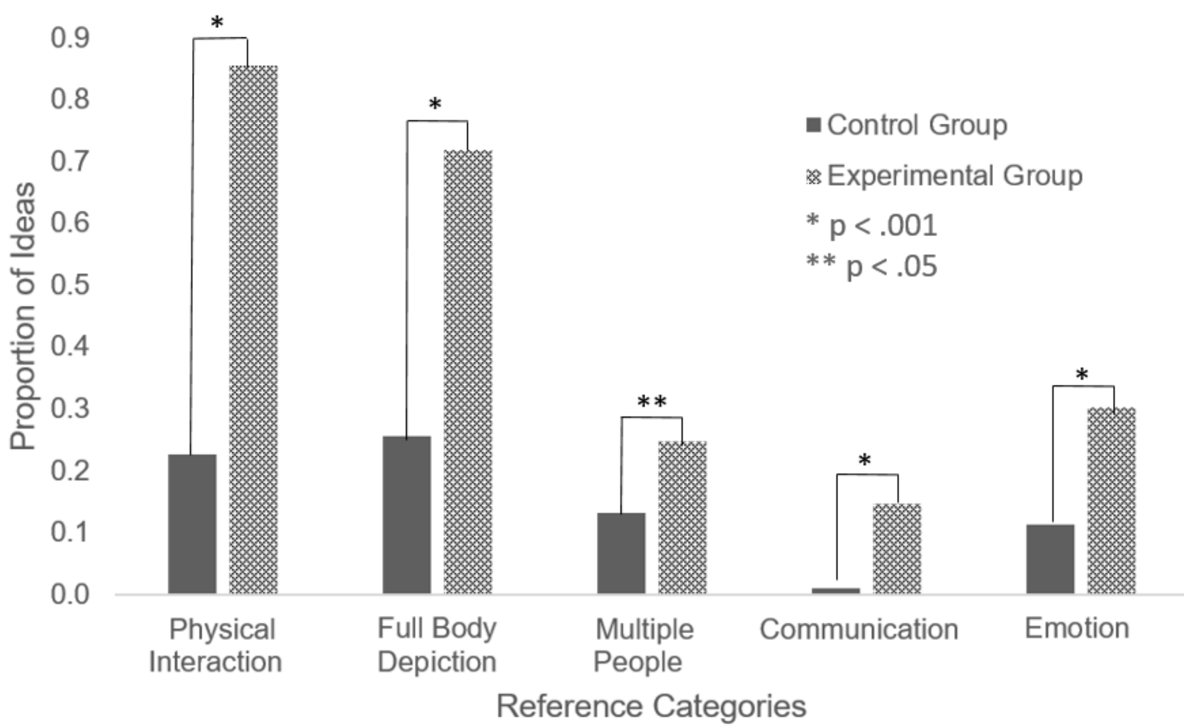


Figure 5: Distribution of sketches between the control group (n = 107) and experimental group (n =89) observed across five identified themes: physical integration, people's full body, multiple people, communication, and emotion

The proportion of all reference categories was significantly higher in the experimental group. Across both groups, physical integration and people's full bodies are the two references categories that occur most often. The greatest change after the intervention occurred with the physical interaction category, indicating that the intervention particularly supported participants in increasing their consideration of how stakeholders interact with the designed solution. Almost no ideas in the control group considered communication between stakeholders, indicating that the intervention to draw people was an important tool in eliciting that consideration for more of the ideas in the experimental group.

Participants' written responses to the two reflection questions ranged from a single word ("Everyone"), to 90 words in length, with an average of 33.8 (17.2) words. Without the intervention, participants generated an average of 2.2 different descriptors (SD = 1.0; range 1 to 5) per concept and the intervention group averaged 3.0 (SD = 1.6; range from 1 to 9). This difference was significant, t(183) = -3.8, $p < .01$. The average length of participant concept reflections was also significantly longer in the intervention group, $t(183) = 3.67$, $p < .001$, as shown in Table 8**.** These findings show that using the intervention changed students' thinking about people in their designs to include more variation, specificity, and elaboration of potential users.

Table 8: Response word counts by group

Group	**Number of Written Responses**	**Minimum Words per Response**	**Maximum Words per Response**	**Average Words per Response**
Control	97	1	76	29.5 (SD = 14.0)
Intervention	88	9	90	38.5 (SD = 19.1)

Responses to the questions "Who is this idea for? Who do you imagine would use it?" were scored with no category observed in more than 34% of responses. This suggests engineers found describing potential users of their designs challenging, or that individuals thought differently about potential users. The 13 categories of people descriptors identified in the analysis are described with examples in Table 9.

Table 9: Descriptors of people identified in participant responses to "Who is this idea for? Who do you imagine would use it?"

Descriptors of People	**Example Quote from Control Group**	**Example Quote from Intervention Group**
People with specific preferences and values	"This is for people who know they will be moving soon and **don't want to hang everything up just to have to take it down**." (C12)	"People who...***are minimalists***." (I1)
People with or without supportive social community	"This idea is for ***people who are bad friends/are such good friends*** that everyone will get a kick out of the …" (C18)	"Someone very disorganized who is going through all their stuff and has ***none to minimal assistance*** packing could use this." (I7)
People who are a particular age	"So most likely ***elderly, young, & those who aren't strong*** enough to move heavy stuff ..." (C6)	"I can imagine a ***young able adult*** using this, since it still requires quite a bit of human movement." (I7)
People who have (or lack) financial resources	"People who want to have a really hassle free move and are ***willing to spend a little more $$ to ease the process***." (C1)	"People ***who have the money*** and need to transport between places where they have to live for a while." (I15)
People with non-monetary skills and resources	"Smart + **social media savvy folk** (age 20-70) likely anyone with a phone can use." (C1)	"I imagine someone who ***just bought a car and*** is planning to use the car and move around a lot would buy this." (I13)
People who own particular possessions	"People ***with bigger furniture/buying furniture***." (C4)	"This idea is for someone moving that ***has a lot of fragile items*** and doesn't want to individually wrap them." (I12)
People with physical environment constraints	"This idea is for people who ***live on the lower floors*** of apt buildings with no elevators." (C18)	"This idea is for people who are moving ***during extreme weather."*** (I13)
People with particular physical ability	***"Weaker people*** too." (C20)	"Who is this for: ages 12+; especially for individuals ***with physical injuries and/or disability***." (I14)
People who are (dis)organized	***"Disorganized people***? ... Not the most space efficient method but need something to have that ***small little organization aspect."* (C4)**	"This idea is for both (moving?) companies as well as a ***well organized amateur.*** I imagine moving companies would use this to ***keep track of inventory...."*** (I18)
People who consider scheduling and stress	"I imagine this is for ***very busy people*** who have the means to use these (services?) while continuing to work or take a vacation to avoid the stresses of (moving?)." (C19)	"All movers, allows automation to help move as many objects to new house as ***quickly and effortlessly*** as possible." (I20)
People who have particular occupations	"I imagine ***businessmen*** using this product." (C7)	"People who has the money and need to transport between places where they have to live for a while. Maybe due to ***occupations.***" (I15)
People who are not the primary user	"Also ***moving companies*** could purchase this to make life easy for their customers." (C8)	"Since it is large and hard to store I would imagine ***professional movers/companies*** would use it the most." (I13)
"All people"	"This idea is for ***anyone*** that is moving." (C21)	"...allows ***all people*** to move their essential furniture most efficiently." (I20)

Three categories showed significant differences in between-groups Chi-Square tests (df=1) Table 10). Specifically, representing people in sketches increased consideration of people's personal preferences, produced more attention to users' physical environments, and decreased claims that designs are intended "for all people." The intervention group also made more references to users' social community, though this difference was marginally significant. While demographic, identity, and cultural differences among people have been noted as important in design (Szalma, 2009), we did not observe any explorations of potential users through specification of citizenship, race, gender identity, sexual orientation, religion, culture, or marital, parental, or partner status.

Table 10: Frequency of specific people descriptions by group

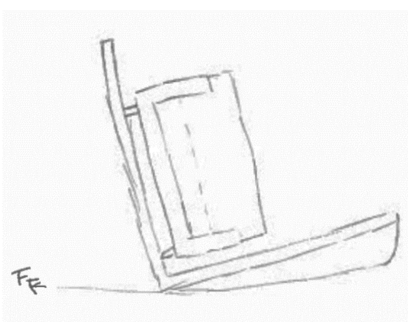
Descriptor Category	Control (%)	Intervention (%)	Difference (%)	Chi Square (df = 1)
Preferences and values	3.09	22.73	19.63	**16.339****
Social community	11.34	20.45	9.11	*2.899^*
Age	12.37	19.32	6.95	1.684
Financial resources	10.31	13.64	3.33	0.487
Non-monetary skills and resources	7.22	10.23	3.01	0.529
Possessions	34.02	27.27	-6.75	0.986
Physical environment	24.74	36.36	11.62	**2.952***
Physical ability	23.71	25.00	1.29	0.041
Organization	13.40	11.36	-2.04	0.176
Scheduling and stress	19.59	21.59	2.00	0.113
Occupations	12.37	5.68	-6.69	2.471
Beyond primary user	11.34	19.32	7.98	2.286
"All people"	22.68	10.23	-12.45	**5.129***
Responses	n = 97	n = 88		

Note: ^p < 0.10; *p < 0.05; **p < .01

These findings show that requiring representations of people in sketches during concept generation increased designers' attention to differences among potential users. Control group participants were more likely to say their concept would work for "all people," even though some sketches and descriptions included more specific user requirements that not all fit. For example, the sketch shown in Table 11 from a control group participant shows a device to load and tip heavy furniture, presumably requiring particular physical strength and mobility; however, the participant describes that the concept works "for anyone." This pattern indicates that students were not attending to relevant differences among people while claiming their concept works for all.

In addition to the question responses, many specifications of people appeared in concept sketches and descriptions. For example, *"*Helping with lifting heavy objects with no good handholds," "Can take/store photos especially for people renting to make sure they have them in case anything happens," and, "To find people to help you move, use an app (move-me) to choose movers in your area so you can find affordable help.*"* These examples from sketch descriptions demonstrate thinking about specific qualities or groups of people during concept generation *before* the reflection questions were presented.

Table 11: A concept claimed to work for anyone ignores potential physical requirements for users

Concept Sketch and Description	**"Who is this concept for?"**
 "This concept is to help turn heavy furniture on its side as to get through narrow areas. One would load the furniture on one side, then tip it using a rope or pulley. Maybe also add some wheels on it to be able to use this to move the furniture without having to lift it?"	"This idea is for anyone...I would imagine anyone would use this as it would hopefully make it easier to move furniture in tight places."

2.4.3 Discussion

In this second study, we found the prompt for students to represent people explicitly in sketches generated important differences in student sketches. Students in the experimental group showed significantly more representations of people across all five categories of interest: stakeholder physical interaction, showing full bodies, drawing multiple people, representing communication between stakeholders, and showing stakeholder emotion. Students generated slightly fewer concepts in the experimental group than the control group, indicating that the intervention may take students more time to implement than their natural, unaided concept generation process.

Our findings identified impacts from the intervention on how designers considered divergent aspects of potential users for their generated concepts. When asked, "Who is this idea for? Who do you imagine would use it?", those asked to represent people in their sketches gave descriptions that differed from the control group in several ways. Although the intervention group produced fewer concepts on average, the intervention did not significantly impact students' productivity. Any slowing may be due to added time for drawing people in sketches, more time spent considering possible users, or some other factor. The intervention group produced longer reflections on who concepts were for, suggesting the intervention promoted intentional, deep thinking about potential users.

The design problem asked designers in both groups to consider physical settings, and the problem content (*help people move households)* encourages awareness of physical constraints. With the intervention, consideration of people's physical settings further increased compared to the control group, suggesting depicting people enhanced attention to the users' setting. Other design problems may prompt attention to other considerations about people's experiences and needs; for example, using the intervention when designing a shared electronic may prompt deeper investigations of people's relationships instead of physical environments. Additional work is needed to investigate how intentional representation of people in design concepts increases attention to human experiences.

The intervention prompted more consideration of people's personal preferences and values in creating design solutions. Incorporating user preferences has been suggested as key to successful designs (Khurana & Rosenthal, 1998; Noland & Phillips, 2010). Zoltowski and colleagues (2012) found that some engineering participants understood human-centered design as keeping users' needs in mind through practices such as including stakeholders across design activities, considering design in context, and developing empathy for users. The simple intervention in this study may similarly provide a strategy for keeping the user in mind during the concept generation through their presence in the sketch.

The findings also suggest more consideration of users' social context or surrounding community beyond the end user by the intervention group. People are often embedded in communities sharing resources, time, and care for each other (Piepzna-Samarasinha, 2018), and attention to community beyond an individual user may be aided by depicting people in designs. Other contexts may be important for other design problems. Burleson and colleagues (2023) described the importance of incorporating many contextual factors during engineering design, such as the socio-cultural, economic, industrial, and political context of users. Considering all people who impact or could be impacted by engineering designs has been supported in prior work (Freeman, 2010; Kujala et al., 2022; Noland & Phillips, 2010).

While participants claimed that their designs worked for "everyone," the intervention halved the frequency of these claims. This suggests the intervention may work to interrupt engineers from generalizing and designing for a single type of user. When engineers imagine a "someone" who will use their new concept, who do they imagine? Hendren (2020, p.12) described designing for 'normalcy' as prolific in engineering and design contexts: "When the average is laden with cultural worth, everything changes: what was common began to be seen as what was 'natural,' and what was 'natural' came to be seen as *right.*" In engineering and design education, assumptions of “normalcy” led to designing for the bell curve and thus for the “average” person, who does not exist (Hendren, 2020; Treviranus, 2019).

One seminal failure from designing for the average occurred in the 1950s with U.S. military aircraft. Engineers measured thousands of pilots, calculating averages for 10 dimensions (e.g., thumb length, torso height). They designed the cockpit to fit those exact average dimensions, only to find that there were *zero* pilots that actually fell into the average range on all 10 dimensions (Rose, 2016). Most of the Western world is designed for this average user, or “normate inhabitant,” which excludes disabled bodies (Hamraie, 2017). Those who do not fit the average have been described as ‘misfits’ by engineered environments not built to include all people (Garland-Thomson, 2011). An intentional focus on diverse users and stakeholders can push designers away from the default “average” view. For example, the Design Justice Network (Design Justice Network, 2018) describes their approach as, “center[ing] the voices of those who are directly impacted by the outcomes of the design process.” This description emphasizes not the average or the norm, but the people *directly impacted,* implicitly requiring a critical evaluation by the designer.

We did not observe a focus from engineers in either group on exploring demographic descriptors such as citizenship, race, gender identity, sexual orientation, relationship status, or religion, perhaps indicating that engineering students need further prompting to encourage consideration of even these obvious variations between people. Some differences in social descriptors appear relevant to the design problem, such as the user’s relationship status (partner, children), and prior work has called attention to the need to consider such differences among potential users (LSA Inclusive Teaching, University of Michigan, n.d.; Szalma, 2009).

Creating a representation of a specific person during design requires choices about their appearance, context of use, and interaction with the design. Future work may investigate how this drawing intervention encourages thinking beyond oneself to other people as intended users. This intervention works to encourage attention to designing for a specific other; however, there are likely many other strategies and methods to promote considering differences in users' needs during the concept generation process. Additional work could also investigate how the intervention interacts with other strategies to center people during design, leveraging the simplicity of drawing people to build on more complex empathy-building strategies.

2.5 Overall Discussion

Overall, the prompt to represent people in sketches during conceptual design led to many improvements in students' ability to consider divergent impacts of their concepts on potential users. The findings from the first study were supported across a greater number of students in the second study. By analyzing the sketches from both studies using the same categorization scheme, we found the effects identified in Study 1 to be replicated in Study 2. Additionally, in the second study we found the intervention prompted a significant increase in students' consideration of communication between potential stakeholders. The difference between studies may be contributed to the different student populations. The first study examined 15 design students across mechanical engineering, user experience, and art and design programs; the second study examined 42 mechanical engineering students. The variation in training may lead to different effects by the intervention. Alternatively, the difference could indicate a trend that simply was not revealed until we had a larger number of students.

We sought to understand if a simple design intervention could help student designers to center people during concept generation. The intervention on its own may not produce nuanced empathy comparable to design research methods, but it appears to be a method promoting incorporation of nuanced and complex information about people during concept generation. Educators and designers can combine this intervention to represent people in conceptual sketches with other strategies to increase empathy with stakeholders.

The findings from the present studies support many of the same conclusions about mental visualizations originated by Dahl and colleagues (2001). Strikingly, working without instructions, student designers rarely show evidence of visualizations of user interactions within their concept sketches. With a simple instruction to depict people in sketches, resulting designs showed varied ways for people to interact with proposed designs. At a conceptual level, the visualization instructions used by Dahl and colleagues (2001) to promote mental imagery of design ideas and people interacting with them showed strong support in the present studies. In Dahl and colleagues' experiments (2001), they prescribed the type of customer to visualize: either a senior citizen or a young woman. We chose not to prescribe, but rather to allow students to define what qualities of people they wanted to represent. This not only allowed for more flexibility in designed solutions, but also provided insight in the qualities students naturally consider when attempting to center people in design.

The advantage of the simple "represent people" instruction in the present studies is that it avoids specifying how the process of mental visualization is to take place; instead, the instruction only specifies the presence of people in the design sketch. This may produce more variation among individuals about how they generated their design concepts and the presence of people within them; however, Dahl and colleagues (2001) also noted a lack of consistency in applying their instructions across students. While our instruction about depicting people is much simpler, it is effective in producing design outcomes with desirable features of deeper consideration of centering people. In further analysis of students' reflections on their concepts from this dataset, we examined more closely what types of people students selected to describe as their end user (Makhlouf et al., 2023). We found that with the intervention, students focused more on peoples' social and physical context of use and their personal preferences and values. We also found the depicting people decreased students' claims that their designs worked for "everyone," suggesting a more nuanced understanding of the ways design decisions impact people differently.

Referring back to the visualization study, there are multiple limitations of that work addressed in our results. The authors of that study contended that the central goal of design is to create design outcomes that "appeal to the end user." Our work questions whether appealing to the end user really is the primary consideration when practicing human-centered design. Rather than focusing on appeal, our work outlines a way to measure what aspects of people's context designers consider, including how a person might interact with the designed solution.

One key finding across both studies reveals that the intervention to draw people helps students consider people beyond just the primary end user. Stakeholders involve anyone who could impact or be impacted by a designed solution (Freeman, 2010). While the primary end user is often the most directly impacted by design decisions, many different areas of literature recommend considering broader stakeholders. Systems thinking literature describes that it is essential engineers consider the many different people affected by implications of their work (Frank, 2000; McKay et al., 2018). Design justice practices recommend engaging with the many people that make up the communities where a design will be implemented (Costanza-Chock, 2020; Design Justice Network, 2018). Our work provides a simple step towards engaging more thoughtfully and intentionally with the impact on various stakeholders early on during concept generation.

2.5.1 Limitations

The studies reported here include a number of limitations. The student sample may limit the generalizability of our results to practicing designers. However, the use of a student sample with broader design backgrounds in Study 1 may enhance conclusions beyond engineering design. In Study 2, the experimental paradigm limited examination of variables that may influence the effects of the depiction instruction for centering people. It is likely that aspects of design problems in domains and the ease of generating solutions will result in the intervention being more or less effective in some circumstances. The challenges of sketching people in designs is an identified problem for engineering students, so it may be possible for those more comfortable with drawing humans may experience greater benefits from the depiction method. In a design context with longer time frames, multiple stages in the design process, teams of designers, and many existing designs may also affect the potential for influence on the observed relationship to centering of people in concept generation.

While the results show that the intervention to draw people support divergent exploration of people in various ways, the experimental designs and analyses do not measure the possibility that the intervention may *limit* divergent thinking more broadly. For example, by requiring students to draw people, the intervention may be directing students to generate concepts that emphasize interaction between people and product, such as consumer products, rather than systems or organizational designs. In that example, the intervention theoretically may bound exploration of potential solutions in some ways while promoting divergence in other areas. Future work may seek to understand the impact of the intervention on the overall diversity of ideas generated.

The first study offers an initial exploration of how students' concept generation is impacted by representing people during a concept generation task. The study included only a short conceptual design session with individual designers using a presented design problem. While this paradigm is standard in studies of design (Shah, Smith, Vargas-Hernandez, et al., 2003), it does not attempt to capture the richness a complete design process more typically involving more research, longer term sessions, and teamwork. The within-participants design (A-B design) is standard in comparisons pre- and post-interventions, and allows comparisons using the same design problem and designer; however, the repeated concept generation sessions with the task including depicting people always came later in the session for all students. Similarly, the think-aloud protocols may not capture the same processes used by designers when working unobserved and without verbalization of their thoughts. Importantly, no evaluation of differences such as the quality of design outcomes was considered in this study, so the differences in consideration of people is not explicitly tied to other outcomes.

Further work is needed to extend the paradigm to include more designers, other design disciplines, and other design problems and contexts. In the second study, we recruited only mechanical engineering undergraduate students whereas in the first study we recruited across three distinct undergraduate design programs. While the five students in each discipline from the first study are not sufficient for drawing conclusions about fields of design and their approaches to representing people, it may be helpful to analyze training materials, methods, and experiences by design discipline so that techniques facilitating the consideration of people during design can be shared across them. With the small sample, important differences in designers' experiences and identities could not be considered. In addition, investigating only concept generation does not reflect how thinking about people changes during extended design work as greater experience and expertise is gained.

2.5.2 Implications

The findings from this study suggest there are positive effects for design students across design fields when intentionally considering people during concept generation. Instructors could ask design students to draw people in all of their concepts in order to reinforce desired attention towards people and encourage more specificity in how they are described and thought of during a design process. Encouraging students to represent people in their concepts is an easy intervention to implement, and it appears to successfully promote deeper consideration of people and contexts during design. Further, making people a focus across design work can support ultimate designs to be appropriate for the people and context in which the design is intended to be situated.

2.6 Conclusion

We examined the impact of an intervention to represent people in conceptual sketches across two experimental designs with student designers. The findings suggest that drawing people during concept generation can help designers think more deeply about who might use and be impacted by their designs. The qualitative analysis of think-aloud protocols in the first study revealed varied changes by student. Some students centered users more explicitly after the intervention; others more deeply considered the emotional or physical context; some shifted attention to the broader community of stakeholders; and some focused on more specific, complex, or personal experiences rather than generic references. Across both studies we observed that the intervention prompted students to consider people's physical interactions and context, their emotions, and interactions between potential stakeholders. The simple step of drawing people can be used in conjunction with other people-focused design practices to support more contextually appropriate design solutions.

This chapter investigated students' divergent thinking about people, advancing our knowledge of how drawing people helps students explore more aspects of users' contexts and interactions with designs. Further, student reflections identify that the intervention explicitly helped students explore more different types of users. Concept generation is not the only time when engineers should explore people and diverse perspectives. In the following chapter, I dig further into how practicing engineers explore diverse perspectives during real engineering projects.

2.7 Acknowledgments

Thanks to Dr. Sophia Brueckner for her support in designing the first study, as well as participants across both studies. Portions of this chapter's results were published and presented at the 2023 International Design Engineering Technical Conference (IDETC) titled *Who is this design for? Promoting consideration of people during concept generation*. The remaining results of this chapter will be submitted as a journal manuscript, and the work was funded by the University of Michigan M-Cubed grant U064092 awarded to Seifert, Daly, Adar, and Brueckner.

Chapter 3 How Do Practicing Engineers Explore Stakeholder Perspectives? Strategies to Support Divergent Exploration in Engineering

The previous chapter investigated student designers' divergent exploration of the people impacted by designed solutions during concept generation. Building on that work, this chapter investigates practicing engineers' divergent exploration of people during real-world engineering projects. The work presented in this chapter was conducted by myself, Thanina Makhlouf, Shanna R. Daly, & Colleen M. Seifert, with contributions to interview design by Shannon M. Clancy.

3.1 Introduction

Human-centered design processes often emphasize accounting for stakeholder perspectives during design work (D. Norman, 2013; Zhang & Dong, 2009). Stakeholders can provide information to improve engineers' understanding of problems and increase appreciation of a solution's implications. Recommended practices encourage engaging with a broad range of stakeholders in order to better anticipate possible solutions (Walther et al., 2017; Zoltowski et al., 2012). This exploration requires a *divergent thinking* process to consider multiple alternative paths and perspectives before selecting one to pursue, shown to produce more innovative outcomes (Ames & Runco, 2005; Wolf & Mieg, 2010). In practice, engineers often associate divergent thinking more narrowly with idea generation (such as by brainstorming), and engineering design education textbooks similarly emphasize exploration during idea generation (Dieter & Schmidt, 2012; Dym & Little, 2004; Zenios et al., 2009). However, divergent thinking can benefit engineering design and problem solving more broadly in many other ways; for example, engineers can explore a diverse set of sources in their contextual research, identify alternative methods to work towards solutions, or understand a problem from multiple perspectives (Daly et al., 2014; Murphy, Clancy, et al., 2022; Treffinger et al., 2002). In this chapter, we focus on divergent exploration of potential stakeholders to better inform engineering design decisions.

To investigate divergent exploration of stakeholders during engineering design, our study sought to understand how practitioners value and consider stakeholders in their projects. We interviewed 20 practicing engineers working on a variety of mechanical engineering projects in industry settings about their experiences during a specific past project where divergent exploration took place. Our goal was to understand how practitioners in the field described the value, barriers, and facilitators of divergent exploration of stakeholders. Understanding how practicing engineers succeed (or not) in stakeholder exploration can guide strategies used in both design practice and education. In engineering design education, the findings can guide course structures, pedagogy, project assignments, and assessment to support intentional use of divergent exploration in recognizing and gathering diverse stakeholder perspectives to inform their work.

3.2 Background

Engineering education prioritizes *convergent thinking*, where students learn to synthesize information and options to arrive at a single 'correct' answer, (Daly et al., 2014; Felder, 1988; Kazerounian & Foley, 2007; Wolf & Mieg, 2010). However, research studies show that divergent thinking, or intentionally considering alternatives, adds value throughout engineering activities (Ames & Runco, 2005; Wolf & Mieg, 2010). Divergent thinking is one aspect of creativity (McCrae, 1987; Treffinger et al., 2002), defined as creating multiple options from a single starting point (Brophy, 2001). In idea generation, divergent thinking supports more innovative design solution options (Daly et al., 2016; Liu et al., 2003; Shah et al., 2000). However, divergent thinking is not limited to design idea generation, and can benefit other aspects of engineering design and problem solving. For example, studies have shown that both students and practitioners used multiple approaches to divergent thinking to take on different understandings of design problems (Murray et al., 2019; Studer et al., 2018). Studies of divergent thinking in both solution generation and problem understanding have shown that the stakeholders considered have impacts on the ways that problems are understood and the types of solutions generated. For example, Studer and colleagues (2018) identified divergent thinking in design problem understanding. In that study, one pattern of problem exploration involved expanding the primary stakeholder group to broaden the problem, leading to a different view of the problem to explore. In another study with engineering students, Murray and colleagues (2019b) identified a strategy for divergence in exploring problems as identifying various subgroups *within* a primary stakeholder group. This intentional focus probed the problem at a deeper level to identify more specific views of the problem. Studies of idea generation have also shown that what stakeholder, if any, designers are considering as they suggest ideas, and the extent of that consideration, impacts the types of solutions considered (Dahl et al., 2001; Murphy et al., 2020, 2021).

Engaging with stakeholders is a key part of engineering design, demonstrated to lead to a more holistic understanding of the people impacted by design decisions and more contextually appropriate designs (Steen et al., 2004; Zhang & Dong, 2009). Engineers may conduct individual semi-structured interviews to gather in-depth and first-hand stakeholder information (Agarwal & Tanniru, 1990; Vredenburg et al., 2002); leverage focus groups with intended users to facilitate specific discussions (McDonagh-Philip & Bruseberg, 2000); immerse themselves in the context of use in order to conduct on-site observations of stakeholders (Ball & Ormerod, 2000; Sommerville et al., 1993); or engage stakeholders as design partners during co-design sessions (Sanders & Stappers, 2008). Intentional engagement with stakeholders has been shown to support the ongoing creative process of building empathy for people impacted by engineering decisions (Bennett & Rosner, 2019; Kouprie & Visser, 2009). Stakeholder engagement can take place across engineering design processes, from problem scoping to development and scaling (Smith & Iversen, 2018). Further, the form of stakeholder engagement employed can impact engineers' feelings of empathy for those stakeholders, with direct contact with stakeholders proving the most effective (van Rijn et al., 2011).

Research has described multiple approaches of engineering designers engaging with stakeholders as well as specific strategies that support gathering rich information from stakeholders (Loweth et al., 2020; Mohedas et al., 2022; Rodriguez-Calero et al., 2023). However, much of the literature concerning stakeholder identification is set in business contexts at the organization- or managerial-level, and does not address engineering practices in exploring which stakeholders to engage (e.g., Rodriguez Serna et al., 2022). Existing guidelines for determining stakeholders suggest identifying anyone who could impact or be impacted by engineering design decisions (Freeman, 2010). Materials tend to emphasize prioritizing stakeholders with the greatest power, legitimacy, and urgent needs in an organization (Mitchell et al., 1997). Thus, the current research may not be easily applicable to engineering decisions, and may be difficult for educators to apply in a design education context. The available guidance for practitioners describes how one's organizational perspective (e.g. organization-centric, issue-centric, or supply-chain-centric) impacts the types of stakeholders identified (Fritz et al., 2018). The size of the business also impacts exploration and engagement with stakeholders; in particular, small businesses can have greater ‘social closeness’ promoting stakeholder relationships (Lahdesmaki et al., 2019). One study found that engineers often overlook ‘indirect’ stakeholders with little influence on technology development, but the indirect users often experience the effects of design implementations (Muller et al., 2022). Pacheco and Garcia (2012) conducted a systematic review of stakeholder identification methods. They found existing guides lack the structure and consistency needed to support engineers in following best practices, suggesting new methodologies are needed.

The gap in knowledge about what impedes or encourages engineers to explore a diverse set of stakeholders in practice is further underlined by the importance of supporting divergent exploration of the stakeholders that should be considered in design work. The set of stakeholders engineers engage impacts engineering outcomes: there are many examples of inequitable designs resulting from engineers neglecting to consult a diverse set of stakeholders. For example, Buolamwini and Gebru (2018) found that darker-skinned women were misclassified up to 34% of the time in commercial facial recognition systems. The datasets informing the facial recognition technology consisted of 79-86% lighter-skinned subjects, suggesting that considering a more diverse group of stakeholders during technology development may support more effective and inclusive design outcomes.

A variety of movements support this need to recognize diverse stakeholders in design work. For example, inclusive design processes suggest engineers need to more critically examine who is included and excluded by their design decisions (Inclusive Design Research Centre, n.d.; Shum et al., 2016). Waller and colleagues (2015) described inclusive design as understanding diversity, and in turn, responding with informed design decisions (Waller et al., 2015). Further, prominent engineering university deans submitted a call for ABET to incorporate diversity, equity, and inclusion principles into their accreditation systems ("Big 10+ Universities Deans of Engineering Letter of Support," 2021), underlining the need for engineers to engage with a broader range of stakeholders. Sippl and colleagues (2022) described how planning technical changes in designs requires identifying all relevant stakeholders to ensure effective project outcomes. Divergent thinking can support consideration of a diverse set of stakeholders.

3.3 Method

The following research questions guided our study:

1) How do practitioners describe the value of exploring stakeholders in engineering projects?
2) What barriers do practitioners perceive to stakeholder exploration?
3) What facilitators do practitioners perceive to stakeholder exploration?

3.3.1 Participants

Participants included 11 men and 9 women, all U.S. engineers. Participants identified their race and/or ethnicity as white (11), Black (5), Latinx (1), Hispanic (1), Southeast Asian (1), and Guyanese (1). Their engineering practice experience ranged from 1.5 to 38 years, averaging 12.4 years (SD = 10.7). Participants worked in engineering industries including automotive, electric vehicle, consumer products, biomedical, human factors, aerospace, commercial trucking, defense, locomotive, energy, and various research and development areas. Participants were identified and recruited using the research team's professional networks, local engineering associations, and snowball sampling from participants.

3.3.2 Data Collection

We conducted individual interviews with each participant. Before the interview, participants were asked to recall a specific experience during a past project where they practiced divergent thinking in their design process: "We're interested in open-ended engineering project experiences where you explored multiple options or perspectives in one or more aspects of the project." Five areas of potential exploration were proposed, including problem understanding, researching stakeholders, problem solving approaches, types of solutions, and project implications. We explicitly requested they consider both successful and unsuccessful exploration during projects.

The individual interviews lasted about 90 minutes, and were conducted virtually with audio recording. First, they described the "big picture" of the past project they selected to discuss, along with its timeline, goals, and constraints. Each participant selected which areas of divergent exploration to discuss and answered the following questions: 1) What did you do? 2) How did you decide to do that? 3) What alternative options did you explore? 4) How did you know you had explored enough? 5) What alternatives did you not explore? 6) Why did you not explore those alternatives? 7) How successful were you at exploring? During interviews, we used follow-up questions to probe for clarification, additional depth, and meaning.

The interview protocol was developed based on recommended practices for semi-structured interviews (Creswell, 1994; Patton, 2002), prior research team experience conducting concrete experience-based interviews with practitioners, and pilot testing with practitioners not in the study. The protocol questions, sequence, and language were revised following the protocol development process, as described by Clancy and colleagues (2022).

3.3.3 Data Analysis

After transcribing the 20 interviews, Makhlouf and I identified interview excerpts related specifically to stakeholder exploration. A few excerpts mentioning "stakeholders" appeared unrelated to exploration processes and were excluded from the analysis.

The analysis began with emergent identification of themes about stakeholders among the 229 excerpts. These themes were identified by Makhlouf and I working independently, and then refined through discussion with the larger research team. We grouped the themes into lists representing the values participants expressed for stakeholders, the factors from the data that supported participants in exploring diverse stakeholders, and the factors that hindered participants from exploring diverse stakeholders. Following recommended practices for thematic analysis (Braun & Clarke, 2006), we iteratively revised descriptions of the identified themes for clarity through multiple reviews of the examples in each.

3.4 Findings

3.4.1 How does exploring stakeholders improve engineering projects?

Practitioners described stakeholder exploration as valuable to their engineering processes. In their past projects, divergent exploration of stakeholders led to better understandings of problems, improved problem-solving processes, risk mitigation, and validation of decisions. These gains led practitioners to talk about stakeholder exploration as a key to their projects' success.

1) Exploring stakeholders **improves understanding** of the problem.

Participants found that exploring stakeholders led to a better understanding of the problems they were working to solve. By engaging with various design engineers, one participant was able to build their knowledge by consulting the people with the most topical expertise:

> "I really communicated with my design engineers…who knew the parts the best. I needed to understand our capabilities. What can we do to these hoses? What can these hoses take? I think I was very good at understanding the problem and checking off all my boxes of what is the problem." (P19)

2) Exploring stakeholders **improves the problem-solving process.**

Participants used stakeholder exploration as a method to more effectively solve problems. One participant saw stakeholder exploration as a way to bring together more expertise, recognizing that one person would not have all the answers:

> "I don't know the product, so to speak. So I don't even know how to explore the options, you know? And so literally the first thing I do is find out as many stakeholders as possible in the process. And I just pull them all together in a meeting and force them to talk. It's less about me exploring the diverse options in this case…I'm sort of pulling diverse people together to explore the options. And that's the best that I can do in helping them problem solve." (P04)

3) Exploring stakeholders helps **mitigate risk.**

Many participants described that exploring a diverse set of stakeholders mitigates risks in engineering problem solving. One participant described how engaging the right people in the early stages allowed her to ensure she was meeting the needs of all those involved in the project, minimizing the chance that she would miss a key aspect of the project:

> "By doing my homework upfront in tying in with the key stakeholders, we really assessed to make sure that we had everything covered from program kick off

through project design, project tests, applications engineering, and then actual customer install on-site, right? So I think by engaging all of those right people along the way, we minimized any negative ramifications." (P08)

4) Exploring stakeholders **validates decisions** and increases confidence.

Multiple participants leveraged stakeholder exploration as a way to gain confidence in the engineering decisions they made. Participants felt that consulting various project stakeholders allowed them to further validate that their decisions were the right ones for the project:

> "Taking into account so many things and just working with a bunch of people from different backgrounds, so like engineers, CAD designers, FEA people, test engineers…We got to a point where it was like, you can't really think of anything else to do to keep analyzing the part. So that gives you a lot of confidence." (P05)

Participants described these four different ways that engaging with stakeholders supported their engineering projects across different stages of their engineering work.

3.4.2 What are the perceived barriers to stakeholder exploration?

Participants described varied circumstances that prevented them from more fully exploring a diverse set of stakeholders: 1) convergence dominance, 2) difficulty managing multiple perspectives, 3) fear of failure 4) fear of increasing risk, 5) in-house expertise, 6) lack of knowledge or clarity, 7) leadership divestment, 8) logistics of exploration, 9) narrow focus, 10) silo organization structure, and 11) uncertainty about exploration process. An example description of each barrier is shown in Table 8.

Table 12: Participants' descriptions of barriers to stakeholder exploration

Barrier to stakeholder exploration	**Participant Descriptions**
Convergence dominance	"And I would always ask the German, what is the plural form of the word 'answer'? And they go, "nobody uses that." There's only one answer in German, right?" (P07)
Difficulty managing multiple perspectives	"…not having so many stakeholders because then you start to get octopus arms and you get pulled in all types of different directions."(P18)
Fear of failure	"…trying to not sound stupid in front of, asking some of the other question between your coworkers because me being a girl from a different country, I was one of the youngest during that time period for that project." (P16)
Fear of increasing risk	"We were limited in our scope by a handful of reputable recognized suppliers. So for risk mitigation, we didn't have the whole world to choose from because it was new technology. It's a brand-endangering product. You don't put it into the hands of a new partner. You choose a tried and true partner. Those partners work with only certain material limitations." (P02)
In-house expertise	"I think it maybe kept exploration a lot more internal because I had someone so close to me who sort of maybe was an expert in it. So I could just really use that one source to learn everything I needed to know." (P11)
Lack of knowledge or clarity	"When the problems are very complex and the scope is not defined easily, it gets more difficult because I am not a subject matter expert. I am only a systems engineer, so it's like I only know what I know. I will say between both projects, when the scope, the stakeholders, the customers are clearly defined and the goals are clearly defined, it's very easy to get the work done. When it's not, that's when you to do a lot of legwork to figure out how to get that done, to get the work done right and in a timely manner." (P20)
Leadership divestment	"Not for anything bad between me and my manager, but old school manufacturing, they don't want to try anything new." (P19)
Logistics of exploration	"So I think we saw like three or four hospitals, but if someone had set up like six initially and they told us like, 'This is going to be a diverse representation of your sample set. This is all you need.' Then we would be better off because we would have more time to gather that information, whereas we were really struggling to get those three or four visits booked." (P09)
Narrow focus	"It's probably at the end you are like involved in your small world in the planning side and you don't look outside. But at the end, everyone is affected by a new plant coming on and being in the area." (P16)
Silo organization structure	"So the difficult part is like even that I have other peers in quality, you never get to work with them." (P16)
Uncertainty about exploration process	"I can't say that I made a conscious decision on that [exploring stakeholders]. Mainly, it came down to, I had a problem I couldn't solve. Go figure it out." (P01)

Participant comments illustrate that not having an established process to direct stakeholder exploration often led to little (or unhelpful) exploration. Further, the perceived difficulty of managing multiple perspectives prevented participants from considering diverse perspectives at all. Similarly, some participants reported that their organizations had no process in place nor even *language* to describe alternatives, making it difficult for individual participants to prioritize exploration.

Another challenge to divergent exploration of stakeholders was that many participants perceived stakeholder exploration as a loss of time and resources, or other risks they were unwilling to take on (e.g., brand-endangering product failures). The perception of risk lies in contrast to the previously stated benefit of stakeholder exploration which is risk mitigation, indicating a disconnect for engineers between a known benefit and managing potential risk. Relatedly, many participants did not more fully explore stakeholders because they did not want the perceived social risk to fail or be embarrassed in front of other coworkers, reported more often by young, women, and minority engineering participants.

Knowledge acquisition or lack thereof appeared to impact stakeholder exploration. When participants held a narrow project focus, meaning they did not engage with nor understand the broader system in which engineering problem solving took place, they failed to engage with stakeholders in the broader project context. A lack of topical knowledge or project clarity prevented divergent exploration due to lack of time and resources to both choose and engage with stakeholders. Relatedly, on multiple occasions participants described how one expert opinion halted exploration of other stakeholders with potential relevance.

Some organizational structures made it challenging to collaborate. Participants felt that the partitioning between engineering teams made it challenging to access expertise in other groups. Similarly, organizations that failed to support engineers in coordinating the logistics of stakeholder exploration took time away from participants' abilities to actually engage with stakeholders. Finally, participants perceived that company management limited or completely halted stakeholder exploration by not prioritizing the time and resources needed for it.

3.4.3 What are perceived facilitators of stakeholder exploration?

Participants described many circumstances that seemed to facilitate and encourage broad stakeholder exploration: 1) curiosity, 2) designated 'exploratory' roles or checkpoints, 3) desire for innovation, 4) leadership investment, 5) novelty, 6) systems thinking, and 7) team collaboration, and 8) team diversity. Each facilitator is illustrated through participant examples shown in Table 9.

Table 13: Participants' descriptions of facilitators for stakeholder exploration

Facilitator of stakeholder exploration	**Participant Descriptions**
Curiosity	"During our visits we were really open-minded and…we gathered so much information…My colleague and I were both really curious." (P09)
Designated 'exploratory' roles or checkpoints	"I think the buy-off of the systems-level people. Yeah. I think it's kind of their role to understand if there's any other people that need to be consulted or anything like that." (P10)
Desire for innovation	"I think my personality really pushes the divergence side a little bit more, which is why I've run into some frustrations with previous projects where this is the way we have to do it. But why can't we try and do it better?" (P12)
Leadership investment	"When they come back to you a third time for the same thing you've been working on that you didn't think had a lot of weight to it. And now they're like name dropping a vice president or a director. You're like, 'oh, okay, got it, got it. Upper level management wants to know about this? This must be something important.'" (P13)
Novelty of problem or solution space	"I'm a young engineer, right? I only know what I've seen and then I only know what I've read. And I've read a lot, like a lot of requirements and stuff like that. A lot of that stuff's transferable because we use global software. But the problem was the stakeholders weren't identified just yet. You can know what you need to do from previous experience and that I think is what a lot of engineers kind of get away with at [Company]. We've done this for years. 'This is the traditional practice. This is standard work,' we say. Until a situation like this where the technology is new and we're still understanding how it interacts with the environment." (P20)
Systems thinking	"People have different vantage points and I mean, even if you're on a manufacturing line, the person that's in front of you, behind you, to left, to the right, whatever that is, you're a customer to each other. You're a teammate to each other. And then you just…from someone that's sitting in accounting and finance to someone that sitting in human resources. These are all part of a team and everybody plays their part. So for me it's just always been looking at the larger picture. Again, going back to, sometimes you need to step back and look at the big picture." (P15)
Team collaboration	"When you're working with a team that's dedicated and focused, you don't mind it. It's something you can really latch onto and you get energized by it actually." (P07)
Team diversity	"That team was successful. I think we had a wide range of experiences coming in. So there were four or five of us primarily working on the project of various ages. Mexican, French, American. People from not just the automotive but from other areas where people come and various…. Everybody was coming in with a different schema and being able to be collaborative." (P02)

Some of the facilitators of stakeholder exploration appeared to relate to organizational structure, some to inter- or intra-personal dynamics, and others to the individual drive of engineers in prioritizing exploration. Newness of technology or limited expertise appeared to increase exploration through collecting new knowledge rather than relying on previous standard practices. Building diverse teams was often reported as a method for exploring diverse perspectives. Positive team dynamics including taking initiative on the work appeared to encourage stakeholder exploration. Curiosity by teams or individuals appeared to be able to drive stakeholder exploration. Similarly, engineers who prioritized stakeholder exploration were influential in facilitating exploration. Systems thinking, or understanding the broader project context, also helped engineers identify and engage with stakeholders. At an organizational level, creating specific roles or checkpoints with a diverse set of people to evaluate stakeholder exploration seemed to encourage and validate it. Finally, if someone in a leadership position requested divergent exploration, more time and resources were devoted towards it.

3.5 Discussion

The findings suggest professional engineers value divergent exploration with stakeholders for a variety of reasons. They reported that exploration of stakeholders improves problem understanding and their problem-solving process and helps to mitigate risk, resulting in greater confidence about decisions. Stakeholder exploration has been shown to be similarly valuable in supporting responsible decision-making for policymakers, especially in avoiding unintended consequences (Fritz et al., 2018). In engineering design, stakeholder engagement has been shown to be an effective part of gathering contextual information (Burleson et al., 2020), a goal related to improving problem understanding. Participants described leveraging stakeholder engagement as a means to improve other aspects of their problem-solving process, which has not been previously described in literature.

Participants' descriptions of past projects revealed parameters that affected their consideration of stakeholders. One of those parameters that worked both in support as well as a barrier was the environment of the organization. Engineers described barriers limiting divergent exploration due to organizational structure, including management, industry norms, seniority, and lack of resources, indicated by the barriers of *leadership divestment, logistics of exploration,* and *silo organizational structure.* Some facilitators appeared to counter described structural barriers: most obviously, while leadership divestment can stop stakeholder exploration, leaders who emphasize the importance of exploration (and provide resources for it) can facilitate its practice during projects. Other organizational barriers and facilitators related to interpersonal dynamics and team norms, such as the barriers of *convergence dominance, in-house expertise, fear of increasing risk, fear of failure,* and the facilitators of *team diversity* and *team collaboration.* An organization that prioritizes more diverse teams or encourages taking on perceived added risks may be more successful in facilitating divergent exploration. Alternatively, an organization relying solely on in-house expertise or one without a systems perspective may struggle in facilitating divergent exploration of stakeholders. These patterns suggest that engineers might benefit from prioritizing broad and exploration knowledge as a way to facilitate stakeholder exploration. For design education, these findings about organizational environment suggest that engineers would benefit from understanding the impact these external factors may have on their ability to explore widely. Further, design educators can seek to inform the engineering managers who have the ability to make changes within their organizations to better structurally facilitate divergent exploration.

The fears of increasing risk or failure have been shown to have complicated effects in other domains. In entrepreneurship, for example, fear or risk or failure have been described as producing both negative limiting consequences and helpful motivation, all seen as part of the ‘entrepreneurial journey’ (Cacciotti et al., 2016). The fear of social failure or embarrassment participants described as limiting divergent exploration may relate to their psychological safety in the workplace. There is little debate that psychological safety in the workplace promotes better team communication, learning, and innovation (Carmeli et al., 2009; Edmondson, 2018). Many women and minority engineers in our study described overcoming a fear of ‘sounding stupid,’ describing key events where their ability to push past the fear improved outcomes. Prior work identified that racial and gender minorities are more likely to experience the work performance and retention consequences of a lack of psychological safety (Halliday et al., 2022; Singh et al., 2013). These patterns suggest that engineering design teams would benefit from prioritizing psychological safety, especially when seeking to promote divergent exploration of many, diverse perspectives.

A notable barrier to divergent exploration of stakeholders was the lack of an explicit strategy or process to support that exploration. Participants often described feeling overwhelmed by too many stakeholders, suggesting uncertainty about managing exploration of alternatives. Many practitioners lacked strategies to ensure they had considered enough stakeholders to make decisions. The lack of an established process for exploring stakeholders led to a variety of problems. For example, one practitioner’s lack of strategy led to missing early engagement with a key stakeholder group. This finding is consistent with literature showing that designers have struggled to navigate stakeholder perspectives that do not align with one another, perhaps causing designers to limit or stop stakeholders engagement altogether (Gambo et al., 2022; Niles et al., 2020; van Lamsweerde et al., 1998). The impact of the lack of an established process on divergent thinking suggests establishing guiding principles for processes may help facilitate exploration of stakeholders throughout project work.

Process-level facilitators that practitioners identified were to take on a systems perspective and implement designated ‘exploratory’ roles or checkpoints. Multiple sources call for an emphasis on systems thinking within engineering (Castelle & Jaradat, 2016; Mote Jr. et al., 2016). Past engineering failures indicate that engineers must understand the system in which they are working, including the social and technical relationships that make up a complex engineering system (Monat & Gannon, 2018). To better facilitate divergent exploration at the process-level, design education may benefit from introducing specific strategies that encourage broad perspective-taking. For example, to support intentional divergent exploration engineering designers might try to frame the problem in a variety of ways (Murray et al., 2019; Studer et al., 2018) to facilitate different takes on who impacts and is impacted by the outcomes.

Participants named their own personalities and preferences as driving or limiting divergent exploration. For individuals, personal qualities such as curiosity, desire to innovate, and team orientation can facilitate the success of stakeholder exploration. Practitioners citing an internal drive to innovate and question norms described prioritizing stakeholder exploration in their projects, sometimes even defying their managers to do so. Treffinger and colleagues (2002) describe that a key aspect of creativity is listening to one’s ‘inner voice,’ further underlining the role of individual agency on facilitating divergent thinking (Treffinger et al., 2002). These results also align with Pacheco and Garcia’s (2012) call for investigation of personality traits on stakeholder identification. Undoubtedly, barriers and facilitators of divergent exploration at the individual, process, and organizational level interact. Organizations can help by building environments where engineers feel safe to take risks or admit they do not have all the answers as well as building in explicit parts of their processes that have divergent exploration goals.

3.5.1 Limitations

This study included twenty interviews with engineering practitioners across various industries. More industry-specific knowledge could emerge by investigating more deeply across engineers from the same industry. However, we found many repeated themes across the practitioners, suggesting saturation of results despite the varied industries. Similarly, each of the engineering projects varied and this study collected only one engineer's perspective on their project. Therefore, we have no external evidence of the projects' 'objective' successes and instead relied on practitioner judgment as to whether a project was successful. External perspectives, such as speaking with other members of the engineers' project teams, could provide a more comprehensive understanding of the success of the process and outcomes of the project.

3.5.2 Implications

While design education points to stakeholder engagement as valuable and important, it lacks guidance about specific strategies to help students learn to execute exploration, recognize what might be missing, and decide when it is adequate. Practicing engineers expressed a lack of known strategies for exploring stakeholders, i.e., identifying a diverse collection of people who impact and are impacted by a problem and its solution, suggesting a gap that further research and development of training pedagogy can fill. To learn how to explore and manage a diverse set of stakeholders, students need experiences driving divergence in stakeholder engagement.

One example of design pedagogy that emphasizes diverse exploration is for instructors to make clear and explicit statement of its value in engineering projects with examples of how engineers report its utility in their past projects. Stories from engineers can make the case for the importance of exploration through examples of how that diverse exploration resulted in "better understanding" and "better problem-solving processes". For example, the story of a construction project that demonstrated early involvement of stakeholders allowed engineers to foster exchange of more creative solutions and a holistic understanding of the context of use (Aapaoja et al., 2013). Relatedly students could engage in two-part exercises where students first develop a project plan for a presented problem on their own and then learn about an expert's project plan. This approach may encourage students to recognize that exploration is helpful in multiple ways, as evidenced by divergent exploration reports by practicing engineers. Further, explicit instruction with accountability on creating diverse stakeholder maps and exploring multiple problem perspectives can support students in achieving more divergent thinking about who their stakeholders are and how they might be impacted.

The environments in which designers engage in projects can be altered to support divergent thinking. For companies, practices can be aligned with exploration by changing reward structures to emphasize collaboration, setting up teams with diverse identities and areas of expertise, facilitating cross-team consultation, framing projects in a broader system context, and investing in the needed time and resources for divergent exploration. For individuals, encouragement for following their curiosity, tolerating feelings of uncertainty about outcome and taking on exploration despite fear of risk and failure, lack of knowledge or clarity. The central message is that the added time spent on exploration is not expected to "pay back" in the same way as linear work processes because, by definition, what might be found and how it might help is unknown. Once divergent exploration pays off through experience, divergent thinking's value within the engineering process has made its case.

3.6 Conclusion

This chapter identifies key opportunities to expose students to perspectives and paradigms that differ or conflict with their current training. Novice engineers may not recognize the value of divergent thinking about who their stakeholders are, and therefore may limit the perspectives they incorporate into their problem solving. Understanding values that practitioners place on divergent thinking and what supports and hinders their divergent exploration of stakeholders can support ways we (re)structure design education. Partnering with diverse stakeholder throughout design work, including community, industrial, and institutional partnerships, ultimately supports more appropriate and successful design outcomes.

This chapter investigated ways that practicing engineers employ divergent thinking to explore stakeholders. The work helps to answer the motivating question of this dissertation, how are we supporting engineers in centering people and diverse perspectives? Identifying tangible barriers and facilitators to stakeholder exploration highlight ways engineering environments and processes influence engineers' ability to diverge. The next chapter looks beyond just stakeholder exploration to understand what influences engineers' ability to diverge across all problem-solving stages.

3.7 Acknowledgements

I would like to thank Shannon M. Clancy for their work on the interview protocol development and all of the interview participants for sharing their experiences with me.

The results of this chapter were presented at the Clive L. Dym Mudd Design Workshop 2023 and are in further review for the International Journal of Engineering Education Special Issue. The work in this chapter was funded by the National Science Foundation (NSF) division of Engineering Education and Centers (EEC) in the CAREER program, grant #1943805.

Chapter 4 Upsetting the Norm of Convergence Dominance: Investigating Practitioner Experiences to Support Divergent Thinking

The previous chapter investigated barriers and facilitators to engineers' divergent exploration of stakeholders. In this chapter, we investigate divergent thinking across all key stages of engineering projects. The work presented in this chapter was conducted by myself, Shanna R. Daly, Thanina Makhlouf, & Colleen M. Seifert.

4.1 Introduction

Divergent thinking is the process of exploring many potential alternative options and diverse perspectives (Brophy, 2001; Runco, 1999). It is often positioned as the opposite of convergent thinking, the process of synthesizing information to come to a single 'correct' answer (A. Cropley, 2006). In engineering, both convergent and divergent thinking are important when solving complex problems (Dym et al., 2005; Wolf & Mieg, 2010). For example, an engineer might divergently explore many potential methodologies to resolve a technical issue, then converge on a single approach to pursue further.

Engineers tend to struggle with divergent thinking, often fixating on pre-existing approaches or solutions and restricting themselves to a single perspective (Ahmed et al., 2003; Crilly & Cardoso, 2017; Cross, 2001; Jansson & Smith, 1991). Prior work shows that people may struggle if they lack an 'openness to experience' or if their thinking styles, attitudes, and personalities otherwise prevent them from engaging with divergent thinking (McCrae, 1987; Runco & Acar, 2019). Beyond engineering, literature shows that employees are inhibited by their organizational environment; obstacles to divergent thinking include a lack of training, organizational culture, physical environment, and workload (Soriano de Alencar & de Fatima Bruno-Faria, 2011).

Most literature on divergent thinking in engineering centers on concept generation, the process of developing a diverse set of potential solutions to a problem (Cross, 2008; Osborn, 1957). Yet, divergent thinking can be useful across other areas of engineering. For example, engineers might take on multiple perspectives of a design problem, explore many potential methods to solve a problem, or seek to understand the broader engineering system made up of social and technical relationships.

Case studies and preliminary research demonstrate that divergent thinking is useful across various stages of engineering problem solving. However, little work has been done to illustrate the circumstances that facilitate or inhibit divergent thinking outside of concept generation. In order to better support divergent thinking, we interviewed a diverse set of mechanical engineering practitioners to better understand how they experienced and practiced divergent thinking across engineering problem solving. By investigating current engineering practitioners' experiences with divergent thinking, we aimed to uncover insights about how to better support divergent thinking.

4.2 Background

Divergent thinking processes involve flexibility and creativity, both key to solving complex engineering problems (D. Cropley, 2016). Divergent thinking was originally studied as an alternative to the convergent-focused IQ tests (Runco, 1999), stemming in part from Guilford's (1950) distinction between divergent and convergent thinking. Divergent thinking was initially believed to be a valid indicator of creativity, which itself has long been an area of study for scholars (Runco, 2010). Over the years it became clear that while divergent thinking is not synonymous with creativity, it can provide useful information about people's potential to generate novel ideas and solve problems creatively (Runco, 2023).

Divergent thinking has been shown to be an important aspect of creativity, meaning that divergent thinking is an aspect of and contributes to creativity, but is not a synonym (Runco, 2010; Vincent et al., 2002). Although research was conducted primarily by cognitive psychologists, divergent thinking research was particularly sparked by an engineering need in the 1950s. Russia's Sputnik satellite had beaten the United States to space (NASA History Division, n.d.), and creativity was seen as the skillset most necessary to meet the increasingly complex challenges facing engineers and technologists (Guilford, 1958). From there, divergent thinking research began to emerge more fully within engineering contexts.

4.2.1 Divergence vs. convergence

In engineering education and culture, there is little debate that convergent analytical skills are prioritized. One study investigated seven engineering courses with the stated goal of fostering creativity (Daly et al., 2014). They found that instruction focused primarily on convergent skills like analysis and evaluation; they found much less evidence of divergent thinking skills like idea generation and openness to exploration. Another study in electrical engineering evaluated course outlines from over 1100 required courses and found less than 2% of courses explicitly focused on creativity (Valentine et al., 2019). A study of engineering instructors and students identified ten 'maxims' of creativity, many of which align with divergent thinking, for example: keep an open mind, ambiguity is good, encouraging risk, search for multiple answers (Kazerounian & Foley, 2007). They found that instructors struggled to effectively teach these maxims of creativity and engineering students felt their education included almost none of them.

The dominance of convergence in both engineering education and culture makes it challenging for engineers to explore alternative approaches, solutions, and perspectives. In regards to engineering culture, several scholars describe ways the convergence is the norm. For one, Cech (2013) described the depoliticization of engineering culture that limits what 'qualifies' as engineering work to purely technical endeavors. In this way, engineering culture discourages exploration of the broader social and political impacts of engineering which are inextricably linked to technical work. Faulkner discussed the impact of the dichotomous ways of thinking that are dominant in engineering, characterized by statements such as: engineering is technical, not social, or engineering deals with hard science, not "people-focused" skills (Faulkner, 2000, p. 759). The dichotomous approach to these topics fail to afford the option that, as is well-defined in literature, engineering is *both* social and technical (Roberts & Lord, 2020; Sladovich, 1991); engineers require *both* technical competencies and ability to navigate social relationships (Lopes et al., 2015). These examples of convergence in engineering culture underline the norms that work against engineers being able to approach engineering work with flexibility and creativity.

4.2.2 Benefits of divergent thinking

Divergent thinking practices in engineering can transform the way engineers approach and solve problems. Divergent thinking plays an important role in producing more innovative and creative design outcomes (Ames & Runco, 2005; Wolf & Mieg, 2010). Training students to think divergently has been shown to support development of creativity (Ritter & Mostert, 2017; Sun et al., 2020). A study of engineering designers showed that participants' initial ideas were most likely already suggested by other participants and therefore not original (Kudrowitz & Dippo, 2013). Beyond idea generation, divergent thinking can help engineers to explore many potential ways to solve a problem (Jonassen et al., 2006). Diverging beyond those initial ideas and solution paths is a key step in increasing innovative outcomes.

Divergent thinking is valuable because it fosters recognition of diverse perspectives. For example, divergent thinking helps engineers to understand the broader engineering system which is made up of both social and technical relationships (Monat & Gannon, 2018). Prior work identified that divergent thinking supported engineers in exploring and incorporating more diverse perspectives (Murphy et al., 2023). Exploring and valuing diverse perspectives is key to supporting more inclusive and equitable designs. Many scholars in pursuit of more equitable design outcomes have called for engagement of diverse stakeholders (Costanza-Chock, 2020; IDEO, 2015; Shum et al., 2016), meaning anyone who could impact or be impacted by a design outcome (Freeman, 2010).

Divergent thinking supports recognition of alternative pathways, affording engineers the opportunity to challenge common engineering assumptions embedded in convergent thinking. For example, convergent thinking assumes that there is a single 'correct' answer to a problem rather than many potential ways to solve a problem successfully (A. Cropley, 2006). Grant (2021) named being able to think flexibly as a core leadership competency. In a motivational interviewing context (p.146), he described that when people are introduced to a binary choice, they often double down on their original perspective (Grant, 2021). In contrast, when people are introduced to a problem with more nuance and are shown a gradient of potential choices, they think of the problem more openly and creatively. Divergent thinking in this way can disrupt convergent assumptions and foster engineers' ability to think flexibly and creatively across engineering problem solving.

4.2.3 Opportunities for divergent thinking in engineering

Research on divergent thinking in engineering has focused primarily on concept generation in design. Concept generation is a key engineering design activity (Dym & Little, 2004), therefore there are many tools that seek to support engineers in exploring a wide variety of concepts. For example, Brainstorming is a common approach that encourages engineers to generate many ideas without judgment either in groups or individually (Osborn, 1957; Paulus & Yang, 2000). Extensive work has been conducted to both develop and understand the impact of these tools on divergently exploring potential design solutions (e.g., Daly et al., 2016b). Research has leveraged concept generation as a useful and relevant measure of how well engineers practice divergent thinking (Runco, 2010). Concept generation has clear ties to divergent thinking, as explicitly identified by comparing divergency and ideation indices (Hyun Lee & Ostwald, 2022). That said, divergent thinking can also be useful across other areas of engineering problem solving, like during background research, identification of stakeholders, problem exploration, and exploration of implications.

When developing problem understanding, engineers might explore by identifying, framing, and defining a need (Paton & Dorst, 2011; Volkema, 1983). Engineers might seek to question the provided problem by taking various perspectives or reframing the problem to understand it differently (Murray et al., 2019; Studer et al., 2018). One study identified 27 different perspectives engineering students took to explore a design problem (Murray et al., 2019). For example, they found engineering students explored the problem by breaking down the primary stated need, by focusing on a particular setting or scenario, or expanding the given scope. Reframing the problem can present challenges to engineers. For example, one business innovation author suggested that it is difficult to reframe the problem in a context where the employee has little power, legitimacy, and allies in support of that exploration (Wedell-Wedellsborg, 2017). It is understood in design that problem understanding will change as work progresses (Dorst & Cross, 2001), but in engineering it is less known what circumstances help or inhibit engineers from questioning, reframing, and otherwise exploring their problem.

Divergent thinking can benefit background research and information gathering. Guilford (1958) described divergent thinking as ‘searching around or changing direction.’ During background contextual research, engineers might ‘search around’ many diverse sources of information (e.g., Salter & Gann, 2003). While not explicitly tied to divergent thinking in the literature, some work exists that describes different types of information that might be useful for engineers to explore. Work by Burleson and colleagues elaborated on a framework for various contextual factors that might be relevant for engineers to research, such as local education and literacy rates, existing institutional practices and procedures, and compatibility with existing technology (Burleson et al., 2023). Systems thinking literature similarly describes that many, diverse forms of information are important to inform engineering decisions, acknowledging the agency of individuals to shape project outcomes (Rebovich, Jr., 2006). Further work is needed to understand what inhibits or facilitates engineers in exploring these different types and sources of information.

Engineering work interfaces and impacts people; as such, engineers have to understand those perspectives in order to be successful. Divergent thinking impacts the variety of perspectives an engineer gathers to inform decision making. Systems thinking literature in engineering describes how for every engineering stage, “the human element has to be considered;” in other words, considering the impact of decisions on various people is key to successful engineering (Frank, 2000). A lot of work on stakeholder identification exists in business management literature (e.g., Rodriguez Serna et al., 2022). Similarly, design literature describes the importance of seeking out many, diverse perspectives to inform design decision (Costanza-Chock, 2020).

Engineers in particular benefit from exploring a wide range of stakeholders to represent diverse perspectives. When engineers fail to account for a diverse set of stakeholders when developing technology, the outcomes have been shown to represent that limited view. For example, a study showed that the datasets informing facial recognition technology included majority lighter-skinned subjects, while darker-skinned women were misclassified by the technology significantly more (Buolamwini & Gebru, 2018). Similarly, engineers developing at-home COVID-19 tests failed to account for diverse potential users, and the tests were therefore unusable for blind people (Morris, 2022). Prior work demonstrated that engineers may struggle to manage many different perspectives (Mohedas et al., 2023; Murphy et al., 2023), and therefore would benefit from more research on how stakeholder exploration takes place in engineering contexts.

Engineers must explore the impacts of their work, including on society and the environment. One review of medical device engineering described that developing the device alone is insufficient to improve health equity; engineers must look beyond the device to engage community stakeholders and investigate contextual factors that might impact device implementation (Rodriguez-Calero et al., 2023). A review of humanitarian engineering programs found a dramatic increase in programs since 2000; the authors described the importance of integrating and embedding education on societal, human, and ethical impacts of engineering practice (J. Smith et al., 2020). One group of scholars forming the Engineering, Social Justice and Peace effort described the need for both reason and compassion in engineering work and education (Catalano & Baillie, 2006). They described how engineers have to understand the ways engineering impacts the safety, health, and welfare of communities, suggesting reflective questions such as: What are the ethical, societal, global, and environmental considerations? Has the suffering or injustice in the world been reduced? Although the need for engineers to explore the many implications of engineering decisions has been described in literature, less work exists to describe how individual engineers go about exploring the many diverse implications of their engineering decisions.

4.3 Methods

The following research question guided our study: What do practitioners report as impacting their divergent thinking during engineering problem solving?

4.3.1 Participants

Participants included 11 men and 9 women all working at the time of the interview as engineers in the United States. Participants identified their race and/or ethnicity as white (11), Black (5), Latinx (1), Hispanic (1), Southeast Asian (1), and Guyanese (1). Their engineering practice experience ranged from 1.5 to 38 years, averaging 12.4 years (SD = 10.7). Participants worked in engineering industries including automotive, electric vehicle, consumer products, biomedical, human factors, aerospace, commercial trucking, defense, locomotive, energy, and various research and development areas. All participants identified themselves and/or their work as within the mechanical engineering field. We selected participants in mechanical engineering to capture experiences of divergent thinking outside of strictly design projects, which have previously been the focus of most divergent thinking research. The relation of each participant to the mechanical engineering field provided both saturation within a single field and breadth across industries and project topics. Participants were identified and recruited using the research team's professional networks, local engineering associations, and snowball sampling from participants.

4.3.2 Data collection

I conducted virtual interviews with each participant. Before the interview, participants were asked to recall one specific experience during a past project where they practiced divergent thinking in their design process: "We're interested in open-ended engineering project experiences where you explored multiple options or perspectives in one or more aspects of the project." We explicitly requested they consider both successful and unsuccessful exploration during projects.

During the interviews, I first asked participants to describe the "big picture" of the past project they selected to discuss, along with its timeline, goals, and constraints. To guide participants, we proposed five potential areas of exploration based on common activities of engineering problem-solving (Dym & Little, 2004): problem understanding, background research and stakeholders, problem solving approaches, types of solutions, and project implications. Each participant selected which areas of divergent exploration were most relevant to their project and answered the following questions for each area: 1) What did you do? 2) How did you decide to do that? 3) What alternative options did you explore? 4) How did you know you had explored enough? 5) What alternatives did you not explore? 6) Why did you not explore those alternatives? 7) How successful were you at exploring?

We designed this series of questions to get more in-depth information about how participants approached their experience. For example, when investigating exploration of problem-solving approaches, we asked participants: 1) How did you go about solving the problem? 2) How did you decide this was the strategy you wanted to use? 3) What other ways did you consider solving the problem other than the strategy you use? 4) How did you know that you had considered enough possible problem-solving strategies for you to move forward with the project? 5) Thinking more broadly, are there multiple different ways the problem could have been approached to reach solutions that were not considered? 6) Why were those strategies not pursued within this project? 7) How successful do you think you were at exploring problem solving strategies?

After discussing participants' selected engineering experience for most of the interview, I asked participants to compare that experience to a different one where they were either more or less successful at exploring diverse options and perspectives. This line of questions interrogated what circumstances made the participant more or less successful at exploration across projects. Finally, I concluded the interviews with broader reflective questions about how their training, engineering experiences, personal perspectives, and engineering environment impacted their ability to explore diverse options and perspectives.

During interviews, I used follow-up questions to probe for clarification, additional depth, and meaning. I audio-recorded the interviews for later transcription and analysis. The research team developed the interview protocol based on recommended practices for semi-structured interviews (Creswell, 1994; Patton, 2002), prior team experience conducting concrete experience-based interviews with practitioners, and pilot testing with practitioners not in the study. The protocol questions, sequence, and language were revised following an iterative protocol development process, as described in more depth by Clancy and colleagues (2022).

Interviews were audio recorded. Interview length ranged from 74 to 105 minutes, with an average of 86 (SD=7) minutes.

4.3.3 Data analysis

I immersed myself in the data through transcribing interviews by hand and doing multiple close readings of all interviews, in accordance with recommended practices in qualitative analysis (Green et al., 2007; Weiss, 1994). The research team employed a multi-pass coding strategy to analyze the data according to the goals of the research questions. In the first pass, two members of the research team identified interview excerpts that described dimensions impacting the practice of divergent thinking across engineering problem solving, coming to consensus on selecting identified excerpts.

In the second analysis pass, the research team inductively categorized the excerpts according to the dimensions they described, generating a preliminary list of dimensions impacting divergent thinking practice. We selected an inductive or 'bottom up' approach in accordance with recommendations (Miles et al., 2014). For example, the following excerpt came from a participant working in the aerospace industry. In this excerpt, the participant discussed a project that required a lot of stakeholder exploration. The project involved a large metal part of a fighter jet which needed to be dipped into a chemical mill (chem-mill) tank, rotated, and pulled out within 12 seconds; the goal was to minimize the amount of hand-grinding needed to clean off slag from previous welding.

> "It was just a lot of sitting down boots on the ground, getting the right people, the stakeholders involved that are going to be involved in this process and getting their feedback because I have zero process for running a chem-mill line. To this day, I still don't. Other than I did one design project on it, I would still go talk to somebody else. And of course the operators themselves go, "well, you know, if you put it on this side, then I can access this and this easier. So when you do the design, make it here." And oh,

by the way, make it this height because, again, they're on a platform. There's tanks and then there's the actual conveyor system above that moves that. So the elevation that they're working on too, you don't want to reach. You have OSHA (Occupational Safety and Health Administration) requirements for overhead work, all these other things…. I would not have understood some of those design issues had I not gone and just had a conversation with these people. So through that – just with a notepad and sketching it out because it's easier than trying to bring a laptop down there at the time – I came up with some ideas and then go back to the computer, fill out the details, and then go back with those people again. And I think that was key to success of this was we had a check process, right? The designer designed, engineer did the engineering and the checker checked and then it got released and then it went and got built. And I didn't follow that process. I said – well, I did because that's how it gets released – but nowhere in the process says, "go talk to the operator." That's just not something – you typically design in a vacuum…I had my one sheet of requirements. Design something that meets those requirements and send it out. That's your job. So getting stakeholders involved really early from the concept was what made that a success."

In this one excerpt, the practitioner identified many dimensions impacting his ability to think divergently. Firstly, he described how he has minimal knowledge on the topic and that this lack of knowledge prompted him to explore various stakeholders who may have additional expertise. He named how his conversations with operators taught him to consider implications he had not previously known about: the platform height, OSHA requirements, and operator arm reach. He described the sketching visualization that helped him to explore potential solutions and engage further with his set of stakeholders. The participant described that his company had a process which to some extent was useful in 'checking' to make sure the implications of each task were considered, but he also described the limitations of that process. He named the convergent norms of his company that made stakeholder exploration difficult – how typically engineers receive a set of requirements and simply work to meet those requirements without additional exploration. The deep exploration of stakeholders required this individual's drive for exploration to go against the standards of his company.

I conducted similar analysis across the remaining 19 interviews to identify the preliminary list of dimensions. The research team went through an extensive process of iterating on and revising the dimensions to most accurately represent the dimensions impacting divergent thinking described by practitioners. We iteratively revised descriptions of the identified dimensions for clarity through multiple reviews of the excerpts in each. We followed suggested practices to iterate many times defining and refining the 'essence' of each dimension in order to best capture the phenomena of interest (Braun & Clarke, 2006; Miles et al., 2014). Throughout the analysis process, I remained the most knowledgeable on the data and did a final close-read pass of all of the data to ensure all relevant excerpts were identified and described accurately. The full analysis process is represented in Figure 6.

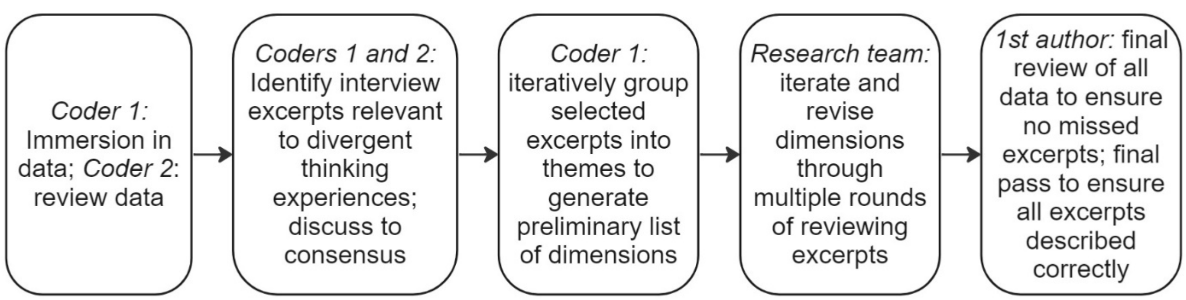


Figure 6: Flow chart of data analysis process

4.4 Findings

We identified 17 dimensions that participants described as impacting their divergent thinking and described them in Table 10. Descriptions of each dimension include how they appeared to facilitate or inhibit divergent thinking for practitioners. We included an additional table in the Appendix with participant interview excerpts illustrating each dimension.

Table 14: Dimensions observed to influence divergent thinking in descriptions of professional engineering projects. Four dimensions appeared only as facilitators or only as inhibitors, thus italicized descriptions denote hypothesized themes we did not directly observe in the data. Example interview excerpts for each dimension are included in the Appendix.

Facilitation of Divergence	*Dimension*	Inhibition of Divergence
Willingness to explore unknowns	**Agency and Openness**	Fear of embarrassment or social failure
Envisions broader system implications	**A Systems Viewpoint**	Narrow focus on independent parts
Clear goals bound deeper exploration	**Clarity in Scope**	Ambiguity confuses exploration
Resources (time, money, team) afford exploring	**Costs of Exploration**	Lack of resources prevents exploration
A designated process builds in exploration	**Designated Process**	Absent a process, uncertainty prevents exploration.
Diverse perspectives offer more alternatives	**Diversity of Perspectives**	Less diverse teams converge on status quo
Unconstrained projects offer more alternatives	**Existing Constraints**	Defined constraints limit seeing alternatives
Scaffolds what/where/how to explore	**Familiarity with Topic**	Assumes more exploration is not needed
Aware of one's own limitations	**Humble Expertise**	Fixates confidently on single path
Lack of knowledge forces exploring options	**Knowledge Limitations**	Limits knowledge of possible options
Encourages and guides exploration	**Mentors and Experts**	Serves role as sole authority
Critical projects drive deeper exploration	**Project Importance**	Small projects do not warrant exploration
Willingness to explore new paths	**Risk Aversion**	Conservative decisions to avoid risk
Stakeholders' interest drives exploration	**Stakeholder Investment**	Exploration stunted from lack of interest
Balances egos, information, options, & risks	**Team Collaboration**	"Silos" limit access to information
Mental & physical visualization reveal impacts	**Tangibility**	*Absence of physicality obscures consequences*
Motivation to change and innovate	**Valuing Divergence**	Convergence incentivized to maintain status quo

While excerpts are included for each dimension in the Appendix, in this section we discuss a subset of the more prominent dimensions and the ways in which they either facilitated or inhibited divergent thinking practice. We also offer a brief discussion of ways that dimensions appeared to interact with one another.

4.4.1 Agency and Openness

One of the more proliferous dimensions facilitating divergent thinking for engineers was agency and openness. This dimension included the individual characteristics and mindsets that prompted engineers to value and push towards divergent thinking. One participant said:

> "I would say to be an effective problem solver that takes a degree of humility, willingness to listen to other people's opinions and entertain their ideas, and a willingness to change your own perspective when necessary" (P6).

A different participant echoed the importance of humility in facilitating their divergent exploration: "It's just like coming and saying humbly, 'I don't know how do to this but I'm willing to learn.'" (P20).

In contrast, practitioners described how fear of embarrassing themselves prevented them from exploring broadly. One practitioner said:

"First of all, I didn't ask many questions…I was shy and I wanted to be good at my job, but I didn't want other people to think I didn't know what I was doing even though as the young engineer, I think you have that. I wanted to learn everything on my own and not sound stupid." (P17)

Although the fear of embarrassment or judgment is very reasonable (and relatable), the practitioner experience highlight the ways that fear prevented her from engaging in divergent, exploratory conversations with many broad stakeholders and expanding her knowledge into unknown areas.

4.4.2 Knowledge Limitations

The most often identified dimension inhibiting engineers was having limited knowledge on their project topic. A lack of knowledge is, perhaps, an obvious barrier to any engineering work:

> "DFMEAs [Design Failure Mode and Effect Analysis] are…intended to catch potential problems, but that's really difficult to do in practice because you can only put in DFMEA things you already know, you know?" (P5).

Multiple participants reflected retrospectively on how they wished they had researched more when they began their projects, describing how their lack of knowledge led them making key mistakes throughout the project. One participant described challenges in opening a new plant:

> "You're launching new equipment, new warehouse, just everything's new. Even to the point where you get there and it's like, oh, we don't even have a janitor…. It definitely would have been nicer to have people more knowledgeable, especially with how to run the machines there" (P15).

In contrast, in other scenarios participants perceived limited knowledge of a topic as a reason to dig deeply into background research, stakeholder engagement, and project implications. One participant described a deep dive into the project history:

> "Because I joined in phase four or five of total six, I didn't have all the history behind it. So one of the important things is learn about the history, learn about what is the status, what is the changes and every time they get the information of all the trials, all the

results, all the reports of the trials, and what were the main changes on every single one of the stages" (P16).

4.4.3 Designated Processes

A more commonly cited facilitator of divergent thinking was companies having designated processes to manage divergent thinking. Some of the processes participants described were explicit strategies like the Eight Disciplines Methodology (American Society for Quality, n.d.-b), Five Whys Technique (Serrat, 2017), Ishikawa Diagrams and Fishbone Diagrams (Cheong Wong et al., 2016; Ishikawa & Loftus, 1990), Failure Modes and Effects Analysis (American Society for Quality, n.d.-a), the House of Quality (Hauser & Clausing, 1988), Is/Is-Not studies (Jing, 2008), Best-of-the-Best and Worst-of-the-Worst studies (Louviere et al., 2015), and the Stanford Biodesign Process (Stanford Byers Center for Biodesign, n.d.). Other participants cited industry regulations or internal standards as scaffolding exploration. Finally, other processes involved having designated 'exploratory' roles or checkpoints, comprehensive internal databases, referring back to fundamental engineering principles, actively asking questions of teammates and other stakeholders, and digging to a root cause in order to best solve a problem.

4.4.4 Costs of Exploration

The most prominent barrier in the data was the logistics required to set up and execute exploration. For example, one participant working in biomedical design wanted to conduct broad exploration of potential hospital environments, but found that to be challenging in the limited time available. She described that it would have been helpful:

> "…if our hospital visits and interviews were setup for us because it did take some time to arrange for those things. And I think that struggle would kind of get to us sometimes…It was disappointing if we weren't getting small and large hospitals or like very rural and urban ones…. If someone had set that up for us than we'd be saving some time and frustration" (P9).

4.4.5 Mentors and Experts

In some cases having a subject-matter expert (SME) to consult facilitated deep exploration by practitioners whereas in others it halted exploration. The data indicated that mentors and SMEs were most valuable when practitioners leveraged them as checkpoints to validate exploration; meaning, rather than asking those mentors to conduct the exploration themselves, they helped practitioners identify areas to explore further given their expertise on the matter. These conversations helped practitioners to 'know what they don't know' and provided guidance to conduct further exploration of background information, problem understanding, problem-solving approaches, stakeholders, solutions, and potential implications. One practitioner stated: "Having other people on your team that have more experience than you to tell you like, 'Hey, did you look at…did you check this? Did you check that?'" (P5)

In contrast, some practitioners perceived their in-house SME as a single source of all information. Rather than exploring multiple sources of information, practitioners assumed that this single person knew everything there was to know. In some cases, practitioners identified these assumptions as a key failure in their project success:

> "I found one person that seemed to know everything. Seemed. Keyword seemed to know everything. And she caught me up to speed on everything from their old company. And I

was like, this is great. I have a full understanding and I kind of dropped it…Very naively, I was like, this is it, this is all I had to do" (P13).

4.4.6 Team Collaboration

Team collaboration was a key facilitator for many participants. It allowed egos to be 'checked at the door,' logistically allowed for better flow of information, supported more engagement with diverse perspectives within and outside the team, and helped people feel more comfortable to take risks. When team collaboration was not available to engineers, they struggled to practice divergence. Silo organizational structures made it challenging for employees from different departments or teams to collaborate with one another. One participant described the impact of the division between her team and others who might have useful advice:

> "The difficult part is like even that I have other peers in quality, you never get to work with them. Besides my training period when I was working with a guy looking for that, you never get to talk that much with them" (P16).

4.4.7 Connections between dimensions

Some of the dimensions appeared to interact with each other. For example, limited team collaboration caused by silo organizational structures appeared to impact individual engineers' systems viewpoint. In other words, when engineers were not afforded a collaborative environment, they seemed to hold a narrow understanding of their project rather than a systems-level view. One practitioner described how he did not account for implications on the supply chain team:

> "It was an assumption that…once I released the drawing, supply would take it over and do their job. They would just handle it. It would get made and it'll go down the line. So it was kind of a 'throw it over the wall and forget about it' type process." (P1)

Further, a narrow viewpoint in some cases appeared to be a symptom of not having a process to manage many different perspectives. Multiple participants described keeping their focus to their immediate teams because of the overwhelm of having "too many cooks in the kitchen" (P12). One participant prioritized "not having so many stakeholders because then you start to get octopus arms and you get pulled in all types of different directions" (P18).

In contrast, it appeared that team collaboration supported systems-level thinking by individual engineers. One participant described the value in "that so-called water cooler talk." He said that having regular casual conversations with his coworkers made it "easier to identify issues with my scope or my understanding and then apply the new skill, technique, or whatever they gave me and go forward" (P20).

Similarly, team diversity appeared to be a dimension contributing to team collaboration. One participant described:

> "Sitting down with all my teammates and looking at the problem and everyone coming up with ideas…having multiple people with their own set of experiences. That's the best. I mean, it's essentially diversity of thought, right? Like just having multiple points of view and having people [who] have solved other problems and bringing that experience with them" (P5).

Naturally, a more diverse team prompted engagement with more varied perspectives and approaches.

Some of the barriers to exploration involved bounding divergent thinking, which did not appear to be always a bad thing. Sometimes providing constraints within which to explore made good business sense. One engineer described limiting their search of potential solutions:

> "I wanted to limit it to the products we had on hand if possible 'cause to me that was the easiest and quickest if we can do this without tooling up anything…New tools costs money. New tools take a lot of time. If we can eliminate the time more than the money, let's see what we have in house. Let's explore those first" (P15).

Limiting exploration in one area seemingly allowed for deeper exploration in alignment with project goals. The nonlinear implications of divergence underline how in engineering problem-solving, both convergent and divergent thinking are necessary.

4.5 Discussion

Some of the 17 identified dimensions that impacted divergent thinking related to knowledge, perspectives, and actions of individual engineers. In contrast, other dimensions described circumstances of the broader engineering organization outside of an individual engineers' control. In this section we discuss our findings under two main claims.

1. **Individual engineers shape divergent thinking practice through their knowledge, perspectives, and actions.**

Many of the dimensions that impact divergent thinking lie within the control of individual engineers. Aligning with prior work suggesting 'metacognition' is a key part of divergent thinking (van de Kamp et al., 2015; Wolf & Mieg, 2010), self-reflection on these dimensions may be enlightening to practicing engineers. The same circumstances appeared to prompt different outcomes depending on the engineers' perspective. For example, in many cases limited knowledge on a topic prompted engineers to explore deeply and broadly. They understood that their knowledge was extremely limited, and therefore worked hard to make up for the lack of knowledge. In other cases, engineers had limited knowledge and, rather than perceiving that as an opportunity to learn, struggled to know what to explore. They did not know their unknowns, and did not seek to find out. It is possible that these dimensions within the control of the individual interact with environmental factors. For example, in an environment where divergent thinking is highly valued and resourced, a practitioner to whom the problem or solution space was novel may leverage that lack of knowledge as a reason to explore deeply. In contrast, in an environment that prioritizes convergence, a practitioner's lack of knowledge may halt exploration entirely.

One dimension that practitioners identified as important to divergent thinking was tangibility: hands-on building and visualization. These early-and-often practices allowed practitioners to test or visualize potential implications of their decisions. It is well known that prototyping is an important tool in engineering design. Prototypes can help engineers catch and minimize negative ramifications of design decisions, advance design projects, and facilitate communication among engineering teams (Dieter & Schmidt, 2013; Ullman, 2010; Ulrich & Eppinger, 2015). Early-stage and low-fidelity prototyping is particularly beneficial for engineers to test out many ideas at low costs (Hadi & Lande, 2019). Prototyping can be more than physically building and testing a product – at its core, prototyping is about testing out an idea. Mental visualization can be seen as an extension of prototyping as a way for engineers to 'prototype' non-tangible aspects of engineering work such as impacts on supply chain or stakeholders. Prior work identified that visualization can help facilitate concept generation (Dahl et al., 2001). To build on the mental visualization that practitioners identified, engineers might benefit from building their skills at prototyping the intangible. Prototyping modalities like mind mapping (Zampetakis et al., 2007), simulation tools (McKay et al., 2022), and storyboarding (Corrie, 2006) can be powerful representations of the intangible aspects of engineers work and may further support divergent thinking.

The dimensions related to individual engineers' perspectives align with previous literature on divergent thinking. One study identified that divergent thinking can correlate with personality, attitudes, and thinking styles (Runco & Acar, 2019). Two studies found that 'openness to experience' predicts divergent thinking (McCrae, 1987; Walker & Jackson, 2014). Our work builds upon previous work by also identifying specific actions and states of knowledge that impact divergent thinking practice. Aligning with our finding that openness supports divergent thinking, Grant (2021, p.27) describes the process of questioning our and others' norms, beliefs, and biases as starting with 'intellectual humility' (Grant, 2021). One study found that intellectual humility is associated with reflective thinking, intellectual engagement, curiosity, intellectual openness, and open-minded thinking (Krumrei-Mancuso et al., 2020). These characteristics have been shown to support knowledge acquisition, further underlining connections to divergent exploration across engineering problem solving. It is possible, therefore, that individual agency and openness as it relates to knowledge manifests as another dimension impacting divergent thinking: humble expertise.

Our work identified that aversion to risk, especially on brand-endangering or legacy products, inhibited individuals' ability to diverge. Literature has shown individuals often revert to rigid and well-known behaviors in stressful work situations (Staw et al., 1981). Especially as convergence is dominant in engineering culture, it makes sense that in high-stress situations individuals would shy away from divergent practices. One study of design professionals found that past experiences with failure can encourage risk-aversion and other convergent ways of thinking (Crilly, 2015), suggesting engineers may benefit from awareness of the impact of past experiences on future divergent practices.

2. **Organizational structure, culture, and processes impact engineers' ability to think divergently.**

Many dimensions impacting divergent thinking related to engineering organizations' structures, processes, and cultures. Organizational structure either facilitated or prevented collaboration; for example, when teams or departments were structurally siloed from one another, collaboration across those gaps was challenging. The engineering culture impacted individual attitudes towards divergence; in particular, when the engineering culture valued divergence, engineering teams and individuals seemed more willing to take on the perceived risk of divergence knowing it would lead to important longer-term benefits. Having designated processes to manage divergent thinking hugely supported engineers; for example, when a team had dedicated checkpoints or designated 'exploratory' roles, there was both accountability and process to ensure teams were sufficiently exploring during engineering problem-solving.

Our findings on the impact of organizational structure, culture, and processes on divergent thinking align with similar findings on creativity. Given the important relationship between divergent thinking and creativity, it can be useful to compare findings between the two. One study investigated aspects of the organizational environment which facilitated or inhibited creativity for employees across a variety of organizations and roles (Soriano de Alencar & de Fatima Bruno-Faria, 2011). Similar to our findings on dimensions that facilitate divergent thinking, the researchers found among other factors colleague support, leadership support, organizational structure and values, resources, and relevant training helped facilitate creativity. Among their inhibitors, they found that leadership divestment, organizational culture, lack of resources or training, organizational structure, and time pressures all barred creativity among employees. One review of organizational creativity found that leadership style, resources and skills, organizational climate and culture, and organization structure all impact creativity (Andriopoulos, 2001).

The most over-arching dimension impacting divergent thinking seemed to be whether divergence was valued in the engineering environment. Nearly all other dimensions could be explained within that. When convergence was prioritized, naturally it followed that there were few processes to facilitate divergence, leadership divested support from divergence, and engineering teams feared taking on the perceived risk of divergence. In contrast, when divergence was valued engineers devoted the time and resources to dig deeply into their project topic, processes were established to facilitate exploration, and engineers prioritized engaging diverse perspectives.

Organizations may find it challenging to support divergent thinking, highlighting the need for more research to develop knowledge and strategies for practitioners. Similar calls to organizations are for “Both/And” leadership or “paradoxical” leadership where leaders are asked to hold multiple, sometime conflicting, truths (W. K. Smith et al., 2016). In the short term, Both/And leadership acknowledges that it can be valuable to have stability and avoid risk; for longer term benefits, however, innovation requires questioning norms, pushing boundaries, and taking risks. Good leaders have to navigate this tension in broader business contexts, and our work demonstrates the same is true for engineering practice. As previously established, both convergence and divergence are important in engineering. Yet, practitioners and organizations lack support and strategies for bringing intention to divergence across engineering problem solving.

4.6 Limitations

The study involved twenty engineering practitioners across various industries. In selecting a wide variety of practitioners, we gained a broad view of the mechanical engineering field. However, the findings do not represent industry-specific circumstances which facilitate or inhibit divergent thinking practice. Similarly, the practitioners represented a wide range of years of experience, but we were unable to identify insights related to specific seniority (e.g., advanced topic experts, new hires, managers). For example, isolating interviews of senior engineering leadership may provide more insights into the role of the organization on engineering practice.

Our method of data collection may have limited insights on certain dimensions of practice identified in the interviews. For example, many participants cited hands-on building and visualization as supporting exploration. In an interview context, it is unlikely that a participant would identify the opposite – that they failed to engage in hands-on building – without being explicitly prompted. Other data collection methods such as contextual observations could provide insights beyond self-reported experiences.

4.7 Implications

To support divergent thinking, engineering education and culture has to challenge the status quo that 'convergence is king.' There is little doubt that convergence is dominant in engineering education and practice, and that convergent analytical skills are prioritized (Daly et al., 2014; Felder, 1988; Kazerounian & Foley, 2007). Therefore, convergence is often the default mode for engineers. Yet, we know that both divergence and convergence are important in engineering (Dym et al., 2005; Wolf & Mieg, 2010). If engineering organizations want to produce more successful engineering outcomes, they need to devote as much infrastructure and cultural value to divergence as they currently do convergence. Engineering leaders need to critically evaluate if their organization values and prioritizes divergence, or if convergence remains the dominant norm.

One suggested implication for engineering practice and education is to leverage the facilitating effects of each dimension as natural 'antidotes' to inhibitors that occur in the engineering environment. As leadership divestment bars engineers' divergent thinking, organizations could ask themselves how they are supporting leadership investment in divergent thinking. Relatedly, educators could consider how they prioritize divergent thinking processes in the curriculum. As a narrow focus by engineers' prevents them from understanding the potential implications of their work, practitioners and educators alike can seek to better support engineers' systems thinking.

Our findings suggest that naming and documenting underlying assumptions and project constraints could similarly serve as a powerful 'antidote' to barriers such as having familiarity with a topic, relying on a singular in-house expert, and fixating on a single path. These barriers, at their core, relate to engineers not examining their assumptions. When engineers have prior knowledge on a topic, they may assume they already know everything they need to know and therefore do not explore the topic more deeply. When engineers assume their in-house expert already knows everything about a topic, they may not explore beyond that singular source of information. When engineers assume their chosen path is going to be successful, they may not explore alternative options. Each of these barriers could be turned into facilitators if engineers interrogate the assumptions behind the decisions they are making.

The suggestion to document assumptions is supported by a recent study on the engineering design process of naval ships that described that one of the most important stages of their process was naming and documenting all underlying assumptions of decisions the team made (Page & Seering, 2023). The study described this process as contentious at first among the team, in part because it required members of the team to justify methods or decisions they were traditionally accustomed to making without question. Naming the assumptions, however, allowed the engineers to questions assumptions that had previously limited design space exploration. Engineering educators could help students develop a process to name assumptions by emphasizing it during course projects or assignments, especially in a capstone context.

4.8 Conclusion

During engineering design, both convergence and divergence are important thinking processes needed to solve complex problems. Yet, engineers often struggle with divergent thinking, especially in engineering environments where convergence dominates. We interviewed 20 engineering practitioners about their experiences with divergent thinking during a professional engineering project. We specifically sought to understand what circumstances facilitated or impeded their ability to divergently explore multiple options and perspectives across engineering problem solving. Through qualitative inductive analysis, we identified 17 dimensions that impact divergent thinking practice. The ways in which these dimensions facilitate or inhibit divergent thinking provide guidance for both individual engineers and engineering organizations to better understand how to support divergent exploration during engineering work and undermine the dominant norm of convergence in engineering.

This chapter sheds light on the broader question of this dissertation which is: how are we supporting engineers in centering people and diverse perspectives at each of those problem-solving stages? In particular, the dimensions of practice show ways that organizations and educators can help engineers resource, prioritize, and establish processes to explore divergently across engineering projects. Divergent thinking, at its core, involves valuing and seeking out many diverse perspectives. Leveraging the dimensions of practiced identified in this chapter, engineers, organizations, and educators can support divergent across all stages of engineering projects.

4.9 Acknowledgements

I would like to thank Shannon M. Clancy for their work on the interview protocol development and all of the interview participants for sharing their experiences with me.

The results of this chapter will be submitted as a journal manuscript. The work in this chapter was funded by the National Science Foundation (NSF) division of Engineering Education and Centers (EEC) in the CAREER program, grant #1943805.

Chapter 5 Discussion: Contributions and Implications

5.1 Chapter summaries

5.1.1 Chapter 2: Where are the humans in human-centered design? Representing people during concept generation

Chapter 2 described a series of in-lab studies with a variety of advanced design and engineering undergraduate students. Building on prior work suggesting mental visualization of end users may help designers, I sought to understand how students represent people in design concepts and how their concepts and thinking change when specifically asked to represent people in their concept sketches. Data included student concept sketches, written concept descriptions, and think-aloud protocols recording students' thoughts while solving the proposed design problem.

I evaluated the data in multiple ways. I developed a qualitative coding scheme to categorize different aspects of ways students represented people in their sketches: emotion, physical interaction, full body vs. part of body, multiple people, and communication between people. These categories provided insights into the aspects of people that students considered before and after the intervention. When evaluating the think-aloud protocol, I analyzed the level of generality with which students talked about people: generally ("everyone," "people"), types of people ("homeowner," "people with a big family"), specific individuals ("my brother"), and themselves as users. Finally, I conducted a deeper thematic analysis of the think-aloud protocols describing changes between the pre-intervention and post-intervention concept generation sessions.

In analysis of the first study's think-aloud protocol, I did not find differences in the level of generality with which students talked about people but did find varied positive changes across students through the thematic analysis. For example, two students who rarely discussed people before the intervention made user descriptions integral to motivating and explaining each concept after the intervention.

Analysis of student sketches demonstrated that students divergently explored various aspects of peoples' interactions with designed solutions after the intervention. In analysis of the first study's sketches, I found the sketches included greater consideration of physical interactions, full body depictions, user emotions, and interactions between multiple people. These findings were replicated across a greater number of students in the second study. In addition, I found in the second study that sketches generated with the intervention to draw people prompted greater attention to communication between potential stakeholders. Further, student reflections explicitly revealed that the intervention helped students explore different types of people. Overall, I found that the simple prompt to "draw people" during concept generation supported deeper thinking about how different types of people are impacted by design decisions.

5.1.2 Chapter 3: How Do Practicing Engineers Explore Stakeholder Perspectives? Strategies to Support Divergent Exploration in Engineering

Chapters 3 and 4 present data from 20 semi-structured interviews I conducted with engineering practitioners about their experiences with divergent thinking. Chapter 3 zoomed in on practitioner experiences with divergent exploration of stakeholders on an engineering project. My analysis sought to understand how practitioners describe the value of exploring stakeholders in engineering projects, and what barriers and facilitators practitioners perceive to stakeholder exploration.

Practitioners described divergent exploration of stakeholders as offering many benefits to engineering problem solving. Namely, stakeholder exploration helps engineers better understand the problem they are working to solve; it improves their problem-solving process by bringing together diverse expertise and ways of thinking; it helps practitioners mitigate risk on complex engineering projects; and it helps practitioners to increase confidence in and validate their decisions.

I identified eight facilitators to divergent exploration of stakeholders: curiosity of individual engineers, having designated 'exploratory' roles or checkpoints, an individual desire for innovation, investment of leadership, novelty of the topic, systems thinking, team collaboration, and team diversity. Practitioners cited eleven barriers to divergent exploration of stakeholders: convergence dominance in the engineering environment, difficulty managing multiple perspectives, fear of social failure, fear of increasing risk, in-house expertise, lack of knowledge or clarity, leadership divestment, logistics, narrow focus, silo organizational structure, and uncertainty about the exploration process. Some of these facilitators and barriers related to the organization, others to interpersonal dynamics, and others to the actions and perspectives of individual engineers. These different levels of analysis suggest various ways engineering practitioners, educators, and organization leaders might further facilitate divergent exploration of stakeholders.

5.1.3 Chapter 4: Upsetting the norm of convergence dominance: Investigating practitioner experiences to support divergent thinking

Chapter 4 presents an analysis of the 20 engineering practitioner interviews investigating experiences with divergent thinking across stages of engineering projects. I proposed five areas of the engineering process for potential exploration by participants: developing problem understanding, conducting background research and identifying stakeholders, selecting problem solving approaches, generating potential solutions, and exploring project implications. I sought to understand what circumstances impact divergent thinking across engineering problem solving. Through an iterative qualitative coding process, I identified 17 dimensions that facilitate or inhibit divergent thinking practice for engineering practitioners.

As examples, three dimensions impacting divergent thinking were having a systems viewpoint, familiarity with the topic, and stakeholder investment. Engineers that held a broad systems viewpoint were able to envision the broader system implications beyond their immediate day-to-day work, understanding that their choices could have unintended consequences. Engineers that held a narrow focus did not know to explore other stakeholders or implications of their work. Familiarity with a topic facilitated divergence by allowing engineers to 'know what they don't know.' Therefore, they had a guide to know what and where to explore. In contrast, familiarity with a topic sometimes inhibited divergence because engineers assumed they already knew everything they needed to know. When important stakeholders such as prominent customers or organizational leadership were invested in exploration, the time and resources needed were devoted to it. In contrast, divestment of stakeholders blocked engineers' exploration.

In sum, there are many dimensions of practice influencing divergent thinking, and they are impacted by both individual engineers and organizational contexts. The findings indicate that engineers have the power to shape divergent thinking practice through their knowledge, perspectives, and actions. At the same time, organizational structures, culture, and processes impact engineers' ability to think divergently. Thus, to support divergent thinking, engineering education and practice has to challenge the convergence dominance currently the norm in engineering.

5.2 Discussion

In Chapter 1, I outlined a key question: How are we supporting engineers in centering people and diverse perspectives across engineering projects? The work presented in Chapters 2-4 begin to answer this question by providing insights on practitioner and student practices, testing the impact of a people-centering intervention, and identifying strategies and recommendations to better support exploration of diverse perspectives. As stated, both convergence and divergence are necessary parts of engineering design, yet engineering education and culture overwhelmingly prioritizes convergence. Thus, in order to find a balance between the two it is essential to investigate ways to support engineers in engaging diverse perspectives. I organize these contributions in three main discussion points: 1) intention towards centering people prompts important changes; 2) individuals can shape engagement with diverse perspectives; 3) organizations impact individuals' ability to explore in engineering projects.

5.2.1 Intention towards centering people prompts important changes

The work presented in this dissertation demonstrates that intention towards centering people during design can prompt important changes in design processes and outcomes. Studies with design students presented in Chapter 2 demonstrate that a simple intervention to "draw people" brings about important improvements in concepts and changes the way students think about the people as they design. Analysis of engineering practitioner interviews presented in Chapter 3 show varying ways that intention towards (or value on) divergent exploration of stakeholders facilitates engagement with diverse perspectives.

One of the most interesting effects of drawing people during concept generation was a shift from thinking about just one primary user to considering more broadly how people may be impacted by a design. Many areas of literature note that the primary user is not the only person impacted by design decisions. For example, systems thinking research states that every stage of decision-making will impact various people, and that it is up to engineers to account for those implications (Frank, 2000). The 'people' could include community members, customers, manufacturers, supply chain coordinators, managers, or engineers working on different parts of the system, depending on the problem context. The design problem we provided to students related to moving households, so additional 'people' students considered included neighbors, moving company employees, and family members. Another example of impact to consider, described by disability studies scholar Piepzna-Samarasinha, is people as part of interdependent 'care webs' where community members give and receive the time, resources, and energy needed to care for each other (Piepzna-Samarasinha, 2018). In this way, it appears insufficient to design for a single end user without considering the ways in which they depend on and contribute to their broader communities. Though we asked students to "draw people" when sketching, we saw in their comments some important changes to address attention toward more diverse perspectives. While centering people does not occur through intention alone, it appears to spark important initial shifts in the ways students think about people through their designs.

It may also be useful to direct designers' attention to particular types of people based on the problem context. For example, inclusive design practices would suggest centering people begins with needs of people with disabilities before extending to other people. A potential prompt for designers might be, for example, "include representations of people who use manual wheelchairs" or "include representations of people with limited use of one of their arms." Further research may explore the impact of such prompts. Inclusive design is particularly concerned with informing design decisions with real, lived experiences of people with disabilities. As such, representational prompts like these might benefit from additional information to support designers as they consider disabilities and avoid unfounded biases in generated concepts. Designers may benefit from combining these representational prompts with data-driven persona spectrums, a tool suggested by Shum and colleagues (2016) to represent the temporal nature of disabilities. Further work is needed to understand how to ethically implement representational prompts across contexts.

The engineering practitioner data from Chapter 3 indicated that individual curiosity and desire for innovation were powerful drivers of stakeholder exploration. In other words, engineers' intention and interest in exploring diverse perspectives tangibly facilitated divergence. Similarly, the intention by leadership to support divergent exploration of stakeholders facilitated its occurrence. When engineers felt their environment and leadership valued exploration, they more easily engaged with diverse perspectives throughout engineering projects.

While the Chapter 2 findings indicate intention promotes centering and exploring people during idea generation, findings from Chapter 3 demonstrated intention motivates exploration across many areas of engineering projects. During background research, one practitioner described how their willingness to explore allowed them to collect richer, deeper information from varied stakeholders. Another practitioner said their willingness to listen to a wide range of people helped in exploring many different approaches to solving problems. She said, “it helps you if you’re open to ideas.” Multiple practitioners’ intentional engagement with people across the entire engineering system gave them more confidence in their later-stage engineering analysis and decisions.

Intention appears to play a large role in exploring diverse stakeholders, so developing strategies to further support practitioners may facilitate that exploration during engineering design. A practitioner might have the desire to center people, but not the process or strategies to do so. Practitioner findings identified having a process to manage divergent exploration of stakeholders facilitated it, while the absence of a known process severely inhibited it. Prior research has identified some practitioner strategies: for example, Rodriguez-Calero and colleagues identified practitioner strategies for using prototypes to engage with stakeholders (Rodriguez-Calero et al., 2020). They found, for example, a practitioner may observe a stakeholder interacting with a prototype in the context of use to test whether the prototype is contextually appropriate. Future work would benefit from describing not only how practitioners engage with stakeholders, but also how they explore stakeholders.

5.2.2 Individuals have the power to shape engagement with diverse perspectives

The findings presented in this dissertation highlight how individuals can impact how people are centered across engineering design stages. Designers and engineers are in positions of power: they make decisions about how the world is built. It is essential that their decisions are informed by the diverse perspectives and lived experiences. In this section, I describe how individuals can engage with diverse perspectives during key engineering design stages:

developing problem understanding, conducting background research, exploring stakeholders, identifying problem solving approaches, generating concepts, and exploring project implications.

When developing problem understanding, practitioner experiences highlighted multiple ways individuals prioritized divergence. Prior work suggested practitioners may adopt varied perspectives to understand the problem differently (Murray et al., 2019). Chapter 3 contributes to this work by identifying stakeholder exploration as a point of divergent processes aimed towards improving understanding of the problem. Engaging people with more topical and varied expertise enriches problem understanding. Chapter 4 describes how mentors and subject-matter experts can facilitate or inhibit engineers' engagement with diverse perspectives. In some cases, engineers assumed their expert source knew all relevant information and did not seek out other sources. In other experiences, mentors scaffolded engineers' exploration based on their prior knowledge to provide guidance for where and how engineers might build problem understanding. Similarly, engineers' perceptions of their own topical knowledge influenced divergence in that some engineers were inspired to explore diverse perspectives because they had little relevant knowledge; in other cases, engineers with little existing knowledge struggled to know what, if anything, to explore.

Background research was also found to provide an opportunity to engage with diverse perspectives. In Chapter 3, one practitioner described "pulling diverse people together to explore the options" as a way to gain more background knowledge from multiple sources. Practitioners described a strong drive for innovation leading to pushing their teams to seek out information on new technologies and engaging experts beyond the initial project scope. Chapter 4 similarly identified humble expertise as a powerful facilitator of exploring background research. Rather than fixating on a single path, humility in knowing one's limitations helped engineers to seek out others with varied expertise.

The stakeholder exploration focus in Chapter 3 is an obvious opportunity for engineers to engage with diverse perspectives. As described previously, individual characteristics like curiosity and desire for innovation facilitate stakeholder exploration, while risk aversion inhibits it. Multiple practitioners described needing to overcome their fear of 'sounding stupid' before they felt able to engage with more varied stakeholders. Overcoming that fear can be challenging, especially for women and people of color who already are more likely to lack psychological safety in the workplace (Halliday et al., 2022).

Engineers may also engage with diverse perspectives when exploring problem solving approaches. Divergent thinking is all about thinking flexibly and creatively, helping engineers to understand problems as open-ended and lacking a single 'correct' answer or way to solve a problem (Runco, 1999). Chapter 3 identified that engineering practitioners divergently explore stakeholders in order to improve their problem-solving process. Similarly, Chapter 4 described the ways that diverse perspectives afford more alternatives to consider when solving problems. During concept generation, the student data from Chapter 2 provide an explicit strategy that individual engineers can leverage to center people more fully. Concept generation is a key engineering design activity influencing all ensuing work (Cross, 2008), suggesting that deeper consideration of people during concept generation can have permeating benefits for later design stages.

A final area of divergent exploration in engineering design is engaging with diverse perspectives when exploring potential project implications. As described in Chapter 4, a systems viewpoint influences whether engineers understand broader implications of their work.

Engineers that engage in systems thinking explore the many people internal and external to their project who may be impacted by design decisions. These findings are supported by prior work describing the networks of people impacted by design decisions, from the end user to the product manufacturer and beyond (Frank, 2000).

5.2.3 Organizations impact individuals' ability to diverge during engineering

The culture and processes of organizations impact individual engineers' ability to diverge during engineering work.

5.2.3.1 Culture

Convergence is the dominant norm in engineering culture. Therefore, organizations must value and devote resources to foster divergence. Data from Chapters 3 and 4 demonstrate that "convergence dominance" as a norm largely impedes any attempts at divergence. In some cases, practitioners were not even afforded language to reflect the possibility of divergence, such as a practitioner working at a German engineering company where the plural form of the word 'answer' was not used. In contrast, when divergence was valued in an organizational culture, engineers felt encouraged to take on the perceived risk of divergence with the support of the time and resources needed.

Team dynamics also played a role in facilitating engagement with diverse perspectives. Collaborative dynamics helped individuals set aside their egos, openly share information, respect varied opinions, and increase their willingness to take risks. Further, diversity on teams naturally supported engagement with more diverse perspectives. Several of the practitioners had advanced in their careers to managerial roles where they may be in the position to impact team development and norms. Individuals and teams can commit to collaboration and improve the conditions for supporting divergence, but organizations also have an important role to play in facilitating that collaboration.

Leadership investment in divergent thinking is a powerful facilitator, while leadership also has the power to stop divergent thinking practice in its tracks. Many practitioners described specific moments where their managers discouraged them from pursuing an unusual or innovative path, suggesting instead the engineers stick to known processes and solutions. In fact, some practitioners described explicitly avoiding their managers to circumvent the barriers they knew they would encounter. In contrast, other practitioners had mentors or leaders who encouraged, valued, and provided resources for divergent practices. Organizational culture influences leaders' behaviors (e.g., Kaur Bagga et al., 2013), suggesting that promoting a cultural value for divergence may elicit their greater investment.

5.2.3.2 Processes

Processes (or a lack thereof) instituted by an organization influence engineers' ability to diverge across engineering projects. Findings in Chapter 3 highlight that when engineers lacked exploration processes for stakeholders, they struggle to do so. Engineers report feeling overwhelmed by managing many conflicting perspectives, and describe being "pulled in all types of different directions." Conversely, when afforded a process to navigate ambiguity in divergence, engineers are much more successful. For example, designated 'exploratory' roles or checkpoints help engineers to ensure they have accountability for as well as support for exploration.

Practitioner findings demonstrate that company processes are instrumental in supporting divergence. Practitioners cited a variety of processes supporting divergence, including internal standards or methodologies like the Eight Disciplines Methodology (American Society for

Quality, n.d.-b), House of Quality (Hauser & Clausing, 1988), and comprehensive internal databases. The success of some processes suggests that if organizations implement them to scaffold and facilitate divergent exploration, engineers will be better suited to engage with diverse perspectives. Prior work identified that questioning existing norms or provided information can be especially difficult when an engineer has little power or support in doing so (Wedell-Wedellsborg, 2017). These circumstances suggest that established processes to promote expectations for divergence in engineering processes are particularly important in supporting younger and minoritized engineers.

5.3 Implications

These research findings have potential implications for supporting engagement with diverse perspectives during engineering projects. Divergent thinking promotes flexibility during every phase of engineering projects, offering benefits beyond the dominant convergent engineering process.

5.3.1 Implications for inclusive engineering design

This dissertation identifies and develops strategies to engage with more diverse perspectives across engineering projects to promote more inclusive engineering and varied design outcomes. My primary motivation with this research agenda was to advance inclusive engineering design and its important implications for the field of engineering design. The design considerations for people have certainly progressed over the last 10 years. For example, Microsoft produced a toolkit which describes inclusive design principles (Shum et al., 2016), IDEO published a *Field Guide to Human-Centered Design* (IDEO, 2015), and increasingly, scholars are studying the ways engineers and designers can engage with people on their projects (e.g. Ku et al., 2015; Rodriguez-Calero et al., 2020). In addition, disabled designers and activists have been centering people in design in inclusive ways for decades (Hamraie, 2017), but there is still a long way to go until engineering processes and outcomes are widely inclusive and equitable.

To advance diversity, equity, and inclusion in engineering design, there are many perspectives academics may take. In alignment with my work on divergence, I believe there is no single 'correct' way to support diversity, equity, and inclusion. I chose to study engineering from an inclusive design perspective because inclusive design is rooted in the lived experiences of people with disabilities. Communications expert and disabled activist Imani Barbarin articulated that disability intersects with every other form of marginalization (Barbarin, 2023). Research has shown that Black Americans, continental Native Americans, and Alaska Natives are more likely to be disabled than any other racial group (Courtney-Long et al., 2017). People who are poor are more likely to be disabled as poverty has been shown to be both a cause and symptom of disability (Goodman et al., 2017; Warren et al., 2023). In these ways, disability can both be a symptom and cause of marginalization. Further, any person at any time can become disabled, as many in the world discovered during the mass disabling event that is the COVID-19 pandemic. For these reasons and many more, disability justice is an important perspective from which to advance inclusion.

Physical representations of people in designs promoted engaging more deeply with important contextual circumstances of potential users. As an example, students more frequently addressed the ways a user might communicate with their social community. This effect seems particularly important for inclusive design because of the ways that disabled people often exist in communities. Disabled scholar Piepzna-Samarasinha described how queer, disabled Black and brown communities in particular rely on “care webs” to receive and offer care to one another (Piepzna-Samarasinha, 2018). Further, they emphasized how these communities of care are essential in imagining disabled futures, a key aspect of disability justice (Piepzna-Samarasinha, 2022). Placing specific attention on the ways people exist in communities offers a pathway to more inclusive engineering design. While many human-centered design processes seek to help engineers consider people more deeply, inclusive design goes further to interrogate which people are being considered. My dissertation begins to identify the different aspects of people engineers are currently accounting for and lays the framework for shifting those aspects to align with the goals of inclusion.

An obvious extension of including physical representations of people during inclusive design is to encourage engineers at all levels to represent specific types of people, such as people who use manual wheelchairs, people who are dyslexic, or people with limited dexterity. None of these groups of people is homogenous, and consideration of these human conditions requires investigation of how people experience them. For example, some manual wheelchair users are ambulatory, meaning they are able to walk to some extent. In this inquiry process, engineers need to learn more about the individuals within the groups for which they design. Designing for specific types of people aligns with published inclusive design recommendations, such as the “solve for one, extend to many” principle encouraging deep understanding of one target community (or individual) and extension into other spaces (Shum et al., 2016). Focusing on specific types of people may also overcome designers’ tendency to conceptualize users as people with similar life experiences as their own (Costanza-Chock, 2020).

An example of the “solve for one, extend to many” principle is the OXO Good Grips line of kitchen tools. Betsey Farber’s re-design of the vegetable peeler began with a mismatch between her arthritic hands and an old metal vegetable peeler (Hendren, 2020; Liston, n.d.). Together with her husband, they iteratively designed what are now ubiquitous black rubber handles extended to many other kitchen tools. Farber's mismatch allowed for a design opening that served not only herself, and not only people with limited dexterity, but ultimately benefits anyone who wants to peel a vegetable.

Further work is needed to understand the impact of encouraging engineers to consider specific types of people (and what 'types of people' engineers should prioritize). The extension of the representational prompt is promising: Further published analyses revealed that students representing people in their designs consider *different* dimensions of people, such as specific preferences and values, social community, and environmental constraints (Makhlouf et al., 2023). Representing people in designs *decreased* students' claims that their concepts would work for everyone, suggesting greater recognition of the ways design decisions impact people differently.

5.3.2 Divergent thinking pedagogy and practice

These studies also have implications for engineering pedagogy and practice. The analyses identified some dimensions impacting divergent thinking practice during engineering projects that are within the control of individual engineers as well as dimensions within the control of engineering organizations.

5.3.2.1 Pedagogy

Engineering educators can easily implement the intervention to draw people during conceptual sketching, both on its own and in conjunction with existing instruction on concept generation. It is easy to imagine other ways to expand on the initial intervention; for example, it may be combined with other people-centered ideation methods. Prior research describes methods for teaching concept generation, such as Daly and colleagues' lesson plans to employ Design Heuristics. These lessons can add in the requirement to represent people within conceptual designs to draw further attention to centering people (S. Daly et al., 2019). Future work might examine the impact of implementing the representation principle across design assignments within a course context. For example, Sangelkar and colleagues found that students had distinct preferences on the concept generation methods employed in a capstone course (Sangelkar et al., 2015).

To help students develop divergent thinking skills in engineering, educators can draw attention to the many dimensions of practice that influence divergent thinking. Educators can help engineers develop an "often and early" prototyping practice, expect not to have all the answers, be comfortable asking for help, and respect that different people will approach and solve problems differently. Educators can also bring awareness of organizational aspects that influence engineers' ability to practice divergent thinking so that engineers can be aware when applying and interviewing for jobs.

Based on these findings, it is essential that engineering education further prioritizes, facilitates, and teaches divergent thinking to the upcoming generation of practicing engineers. Engineering education influences future engineering culture (Carberry & Baker, 2018; E. Cech, 2014), and this dissertation describes the ways that engineering culture shapes divergent thinking practices. Engineering educators must name the need to overhaul engineering culture in order to upend the traditional values that limit engineering work and exclude people with underrepresented identities (Carberry & Baker, 2018). Further, the definitions of engineering must be expanded to include divergent thinking practices in what 'counts' as engineering. This last point in particular echoes the findings of this dissertation: divergent thinking defines effective engineering practice as much as convergent thinking.

5.3.2.2 Practice

Engineers and engineering organizations can incorporate recommendations from this thesis through self-reflection, learning and establishing processes to facilitate divergent thinking, and encouraging divergent practices in their environments. Self-reflection is an important part of engineering practice. Previous research emphasizes that practitioners benefit from "reflection-in-action," the process of recognizing lessons learned by doing (Schön, 1983, 1987). My work suggests that engineers may benefit from asking themselves, "Am I leading with humility to learn what I don't know? Can I change my perspective and explore unknowns? Do I understand my work within a broader system, and have I considered implications of my work?"

Leadership in engineering organizations may similarly benefit from considering how their environment and practices impact divergent thinking: "Are we providing clear goals and constraints to bound deep exploration? Have we provided the necessary time, money, and logistical support for divergent thinking practices? What processes are in place to help facilitate exploration? Are we hiring and compiling diverse teams? Are we providing engineers with a network of mentors and experts to support exploration? Are we helping engineers feel safe to take risks? "

Engineers can prioritize divergent thinking when established processes and practices support them. One practice that supports divergent thinking, hands-on building and visualization, helps reveal potential implications of engineering decisions. Prototyping has long been recognized as an important tool in engineering. Prior work has emphasized the importance of prototyping early and often, describing the ways physical building is key in helping engineers envision complex systems (Carleton & Cockayne, 2009). Our work builds on prior work by uncovering the ways that prototyping and visualization support divergent thinking practices and shows how individual agency and openness drive divergent thinking.

Engineering organizations can advance engagement with diverse perspectives by outlining processes and logistical support to navigate the ambiguity of considering multiple perspectives. Practitioner experiences illuminated organizational features like internal databases, standards, and regulations in facilitating exploration. Investment in these features can support engineers in divergent thinking practices.

5.4 Conclusion

Divergent thinking is an essential part of successful engineering work, yet engineering education and culture predominantly emphasizes convergent thinking skills. This dissertation investigated divergent thinking as a tool to more intentionally 'center' people in design and explore diverse perspectives in engineering projects. These studies offer actionable strategies and dimensions of practice to support engineers' divergent thinking practices. Centering people during concept generation through their literal presence in designs changed students' thinking in important ways. Experiences of practicing engineers revealed facilitators and inhibitors of engagement with diverse stakeholder perspectives. Finally, engineers described dimensions of their own processes and those of engineering organizations that influenced divergent thinking practice. Overall, the thesis establishes underlying practices needed to supporting engineers in centering people and considering diverse perspectives to support inclusive engineering design.

Appendix

Appendix Table 1: Examples of interview excerpts for each dimension that impacts divergent thinking practice

Facilitation Example Protocol	***Dimension***	**Inhibition Example Protocol**
“I would say to be an effective problem solver that takes a degree of humility, willingness to listen to other people's opinions and entertain their ideas, and a willingness to change your own perspective when necessary.” P6	*Agency and Openness*	“Yes. Because I was scared. I sat back and learned instead of being upfront, right? And you can't really learn if you just sit…well, you can learn sitting back and you can learn and you can observe people. But that's when it was so overwhelming to be on site of the customer. You have all these engineers who know what they're doing. So I sat back.” P17
“Well now we're talking to facilities people, we’re talking to general managers of the area, operations managers, the actual operators because they're going to have to know how to use this when it comes in and be comfortable with it.” P1	*A Systems Viewpoint*	“Yeah, I mean, on the daily when you’re just doing your daily task, you don't always recognize the problems that you're solving sometimes. You’re looking at more of a micro level at times ....” P18
“And I gotta tell you it is very, very easy to keep thinking of “what-if” scenarios and having this infinitely long set of tests that I would love to do. So having these constraints early on definitely made me satisfied that I did my due diligence and…I did enough.” P1	*Clarity in Scope*	“It was also something where my team didn't even understand the scope of the ask. So they couldn't even set me up in a way where we could have predicted that ask.” P13
N/A	*Costs of Exploration*	“Balancing out the need to maintain a schedule and actually make a decision versus finding a perfect design. I don't know…perfection is kind of the side of engineering. In general it was like, it could always be better and I want to figure it out. But yeah, there's I guess not really that endless time to do it.” P10
“A goal of the Stanford Biodesign process, which is the method that we're supposed to use, is to try to remain unbiased. So when we do the observations and interviews, we want to try to identify from the user's perspective what the problem is.” P9	*Designated Process*	“This is the one I might have no answer for you because I don't know. Because it's not like we specifically laid out a strategy that would have been best.” P3
“Sitting down with all my teammates and looking at the problem and everyone coming up with ideas or things that should be looked into that we should be considering… I mean, it's	*Diversity of Perspectives*	“People with whom you collaborate are not always widely varied in their position or in their background or in their education.

essentially diversity of thought, right? Like just having multiple points of view and having people [who] have solved other problems and bringing that experience with them." P5		Most of the time we're in solving problems with people that think a lot like us." P2
N/A	*Existing Constraints*	"In this instance for us, coming up with a completely new concept was not…like it was just not an option. Right? ... But if you already have something that you're starting out with, that really limits your options and you have to work within those constraints." P5
"My advice, again, if anyone's listening, is to humble yourself. I have no problems whatsoever talking to the injection molding supplier because they are experts at injection molding and tell me how to improve the design of this part." P1	*Humble Expertise*	"I didn't explore that many. I don't know if that doesn't make it successful. But I also think like we didn't spend too much time relatively speaking just kind of like spinning our wheels and like trying to find other things. I think we found something that worked and kind of moved forward." P10
"So a little bit of knowing already the product, being that this was my maybe fourth or fifth project. So I already had a little bit of experience working with this product, so you already understand where are the key items to check and the main points [to] check." P16	*Familiarity with Topic*	This time around, we assumed the problem was solved. So since, since it was all, 'this is easy,' it was just, go do it, get it done. And not taking the time to do the actual due diligence." P1
"Initially, I wasn't quite sure what I was gonna do. Because at that point I had never run a test organization. Okay? So first of all, somebody show me what the equipment looks like, right? And then I started reaching out to do my research and talk with my connections. I met with my boss first and said, 'What are we talking about? What is on your mind? What does 'done' look like for you?'" P8	*Knowledge Limitations*	"So I think like the limited knowledge in the beginning was sort of a hindrance because I learned more as I went on and became an expert in it. But at the beginning when I was making the big like project-impacting decisions and problem-solving strategies, I didn't have all the expertise that I did at the end. So if I had known more at the beginning, maybe I would have had even more creative problem-solving strategies." P11
"Being around someone who's been through it 20 plus years. Going to them and asking for their advice... they give you insight and their perspective and then they'll say, 'Oh, I would look for this here… That's fishy to me. Ask about this.' And then just building up that list of due diligence." P18	*Mentors and Experts*	"I think it maybe kept exploration a lot more internal because I had someone so close to me who sort of maybe was an expert in it. So I could just really use that one source to learn everything I needed to know … But like for this one, I didn't need to go that broad because I had something so close." P11
"So brake systems are safety critical…So one of the nice things about it is that you can really go deep and people want you to go deep because any risk is really bad, right? The consequences of having a bad system are potentially, I mean, you're talking about people could lose their life." P5	*Project Importance*	"We just felt like the impact of that particular problem was smaller than what we could potentially impact if we solved a different problem." P9
N/A	*Risk Aversion*	"So for risk mitigation, we didn't have the whole world to choose from because it was new technology. It's a brand-endangering product. You don't put it into the hands of a new partner. You choose a tried and true partner. Those partners work with only certain material limitations." P2

“When they come back to you a third time for the same thing you’ve been working on that you didn’t think had a lot of weight to it, and now they’re like name dropping a vice president or a director. You’re like, ‘oh, okay, got it, got it. Upper level management wants to know about this? This must be something important.’” P13	*Stakeholder Investment*	“But then when we presented to the leadership team, they rejected all of it and their solution was to, “well, just have a meeting with us to make sure and we’ll tell you whether you can move forward or not.” And we did what they said and we continued to have the same problems...I can't explain why someone would just ignore that..” P15
“And, you know, when you have a really strong functioning team, the egos are checked at the door and, and everybody just says, ‘let's get it done.’ And everybody's trying to get the same end result. And that definitely comes into play for a good launch versus a bad launch.” P7	*Team Collaboration*	“So a bunch of these discussions were happening between maybe two teams other than the four I described earlier. Only two teams were talking at a time and having parallel but slightly different conversations. And it took a while to realize, oh, other teams are involved in these discussions. Let's all get together and scope it together so we're completely on the same page and timelines align.” P12
“Some of [the implications] are defined. Some of them I would just walk through the process. So in an installation or an assembly – and this is why I think every engineer should, build their first prototype so that they can see all the stupid things that they did. And myself included.” P6	*Tangibility*	*N/A*
“Whereas this new division, they're like, ‘Hey, you're only five years into your career. Why don't you try and give a stab at this and see what you come up with. And then we'll both learn and fail from that together.’” P12	*Valuing Divergence*	“I think a lot of it was just kind of company culture. Not really wanting to understand problems fully or just like having pressure to keep costs low. So therefore, you don't spend as much money on testing and validation.” P5

Bibliography

Aapaoja, A., Haapasalo, H., & Soderstrom, P. (2013). Early stakeholder involvement in the project definition phase: Case renovation. *International Scholarly Research Notices: Industrial Engineering*. http://dx.doi.org/10.1155/2013/953915

Adams, S., & Fortenberry, N. L. (n.d.). *Strategic priorities: 2020-2021 to 2022-2023*. American Society for Engineering Education. https://www.asee.org/about-us/who-we-are/Our-Vision-Mission-and-Goals

Agarwal, R., & Tanniru, M. R. (1990). Knowledge acquisition using structured interviewing: An empirical investigation. *Journal of Management Information Systems*, *7*(1), 123–140.

Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11.

Allen, M. S. (1962). *Morphological creativity: The miracle of your hidden brain power; a practical guide to the utilization of your creative potential*. Englewood Cliffs, N.J., Prentice-Hall. http://archive.org/details/morphologicalcre00alle

Alzheimer’s Association. (2018, July 24). We are Alfred: VR helps students experience dementia. *Medical Design & Outsourcing*. https://www.medicaldesignandoutsourcing.com/we-are-alfred-vr-helps-students-experience-dementia/

American Society for Quality. (n.d.-a). Failure mode and effects analysis (FMEA). *Learn about Quality*. Retrieved September 22, 2023, from https://asq.org/quality-resources/fmea

American Society for Quality. (n.d.-b). What are the eight disciplines (8D)? *Learn about Quality*. Retrieved September 22, 2023, from https://asq.org/quality-resources/eight-disciplines-8d

Ames, M., & Runco, M. (2005). Predicting entrepreneurship from ideation and divergent thinking. *Creativity and Innovation Management*, *14*(3), 311–315.

Andriopoulos, C. (2001). Determinants of organisational creativity: A literature review. *Management Decision*, *39*(10), 834–840.

Artacho, M. A., Ballester, A., & Alcantara, E. (2010). Analysis of the impact of slight changes in product formal attributes on user's emotions and configuration of an emotional space for successful design. *Journal of Engineering Design*, *21*(6), 693–705. https://doi.org/10.1080/09544820902875058

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

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education*, *87*(2), 121–132.

Ball, L. J., & Ormerod, T. C. (1995). Structured and opportunistic processing in design: A critical discussion. *International Journal of Human-Computer Studies*, *43*, 131–151.

Ball, L. J., & Ormerod, T. C. (2000). Applying ethnography in the analysis and support of expertise in engineering design. *Design Studies*, *21*, 403–421.

Barbarin, I. [@crutches_and_spice]. (Director). (2023, August 14). *And thus themselves as well [Video]* [TikTok]. tiktok.com/t/ZT8MN2vGJ

Bearman, M., Palermo, C., Allen, L. M., & Williams, B. (2015). Learning empathy through simulation: A systematic literature review. *Society for Simulation in Healthcare*, *10*(5), 308–319. https://doi.org/10.1097/SIH.0000000000000113

Bendelow, G., & Williams, S. (1995). Pain and the mind-body dualism: A sociological approach. *Body & Society*, *1*(83). https://doi.org/10.1177/1357034X95001002004

Bennett, C. L., & Rosner, D. K. (2019). The promise of empathy: Design, disability, and knowing the "other." *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–13. https://doi.org/10.1145/3290605.3300528

Berlin, C., Bligard, L.-O., Babapour Chafi, M., & Eriksson, S. (2021). Development of a stakeholder identification and analysis method for human factors integration in work system design interventions—Change Agent Infrastructure. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *32*(1), 151–170. https://doi.org/10.1002/hfm.20910

Big 10+ Universities Deans of Engineering Letter of Support. (2021, March 31). *ABET: Diversity, Equity, & Inclusion*. https://www.abet.org/about-abet/diversity-equity-and-inclusion/

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*, 77–101. https://doi.org/10.1191/1478088706qp063oa

Brophy, D. R. (2001). Comparing the attributes, activities, and performance of divergent, convergent, and combination thinkers. *Creativity Research Journal*, *13*(3 & 4), 439–455.

Brown, B. (2021). *Atlas of the Heart*. Random House.

Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design Issues*, *8*(2), 5–21.

Buolamwini, J., & Gebru, T. (2018). Gender shades: Intersectional accuracy disparities in commercial gender classification. *Proceedings of Machine Learning Research*, *81*, 1–15.

Burleson, G., Herrera, S. V. S., Toyama, K., & Sienko, K. H. (2023). Incorporating contextual factors into engineering design processes: An analysis of novice practice. *Journal of Mechanical Design*, *145*. https://doi.org/10.1115/1.4055780

Burleson, G., Sienko, K. H., & Toyama, K. (2020, August). Incorporating contextual factors into a design process: An analysis of engineering for global development literature. *Proceedings of the ASME 2020 International Design Engineering Technical Conference*.

Cacciotti, G., Hayton, J. C., Mitchell, J. R., & Giazitzoglu, A. (2016). A reconceptualization of fear of failure in entrepreneurship. *Journal of Business Venturing*, *31*, 302–325. http://dx.doi.org/10.1016/j.jbusvent.2016.02.002

Carberry, A. R., & Baker, D. R. (2018). The impact of culture on engineering and engineering education. In *Dori, Y.J., Mevarech, Z.R., Baker, D.R. (Eds). Cognition, Metacognition, and Culture in STEM Education: Innovations in Science Education and Technology* (Vol. 24, pp. 217–239). Springer, Cham. https://doi.org/10.1007/978-3-319-66659-4_10

Carleton, T., & Cockayne, W. (2009). *The power of prototypes in foresight engineering*. International Conference on Engineering Design, Stanford, CA.

Carmeli, A., Brueller, D., & Dutton, J. E. (2009). Learning behaviours in the workplace: The role of high-quality interpersonal relationships and psychological safety. *Systems Research and Behavioral Science*, *26*, 81–98. https://doi.org/10.1002/sres.932

Carroll, J. M. (1997). Human-computer interaction. *International Journal of Human-Computer Studies*, *46*(4), 501–522. https://doi.org/10.1006/ijhc.1996.0101

Castelle, K. M., & Jaradat, R. M. (2016). Development of an instrument to assess capacity for systems thinking. *Procedia Computer Science*, *95*, 80–86. https://doi.org/10.1016/j.procs.2016.09.296.

Catalano, G., & Baillie, C. (2006). Engineering, social justice and peace: A revolution of the heart. *ASEE Annual Conference & Exposition*.

Cech, E. (2014). Culture of disengagement in engineering education. *Science, Technology, & Human Values*, *39*(1), 42–72.

Cech, E. A. (2013). The (mis)framing of social justice: Why ideologies of depoliticization and meritocracy hinder engineers' ability to think about social injustices. *Engineering Education for Social Justice*, 67–84.

Center for Socially Engaged Design. (2020). *Socially Engaged Design Process Model*. https://csed.engin.umich.edu/socially-engaged-design-process-model/

Charmaz, K. (2006). *Constructing Grounded Theory: A practical guide through qualitative analysis*. Sage.

Cheong Wong, K., Zhi Woo, K., & Hui Woo. (2016). Ishikawa Diagram. In *O'Donohue, W., Maragrakis, A. (eds) Quality Improvement in Behavioral Health* (pp. 119–132). Springer, Cham.

Clancy, S., Murphy, L. R., Daly, S. R., & Seifert, C. M. (2022). *Developing an interview protocol to elicit engineering students' divergent thinking experiences*. 2022 ASEE Annual Conference & Exposition.

Clarke, V., & Braun, V. (2013). Teaching thematic analysis: Overcoming challenges and developing strategies for effective learning. *The Psychologist*, *26*(2).

Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10.1177/001316446002000104

Corrie, V. der L. (2006). The value of storyboards in the product design process. *Personal and Ubiquitous Computing*, *10*(2), 159–162.

Costanza-Chock, S. (2020). *Design Justice: Community-led practices to build the worlds we need*. MIT Press.

Courtney-Long, E. A., Romano, S. D., & Carroll, D. D. (2017). Socioeconomic factors at the interseciton of race and ethnicity influencing health risks for people with disabilities. *Journal of Racial and Ethnic Health Disparities*, *4*, 213–222. https://doi.org/10.1007/s40615-016-0220-5

Creswell, J. W. (1994). *Research design: Qualitative and quantitative approaches. Thousand Oaks*. Sage.

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

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

Crilly, N., & Cardoso, C. (2017). Where next for research on fixation, inspiration, and creativity in design? *Design Studies*, *50*, 1–38.

Cropley, A. (2006). In praise of convergent thinking. *Creativity Research Journal*, *18*(3), 391–404.

Cropley, D. (2016). Creativity in engineering. In Giovanni Emanuele and Sergio Agnoli (Eds.), *Multidisciplinary contributions to the science of creative thinking*. Springer.

Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. In C. Eastman, W. Newstatter, & M. McCracken (Eds.), *Design Knowing and Learning: Cognition in Design Education* (pp. 79–103). Elsevier.

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4th ed.). Wiley.

Dahl, D. W., Chattopadhyay, A., & Gorn, G. J. (2001). The importance of visualisation in concept design. *Design Studies*, *22*(1), 5–26. https://doi.org/10.1016/S0142-694X(99)00028-9.

Daly, S., McKilligan, S., Leahy, K., & Seifert, C. (2019). *Teaching Design Innovation Skills: Design Heuristics Support Creating, Developing, and Combining Ideas* (pp. 37–60). https://doi.org/10.1007/978-3-030-17134-6_3

Daly, S. R., Mosyjowski, E., & Seifert, C. M. (2014). Teaching creativity in engineering courses. *Journal of Engineering Education*, *103*(3), 417–449.

Daly, S. R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016a). Comparing ideation techniques for beginning designers. *Journal of Mechanical Design*, *138*(10), 101108. https://doi.org/10.1115/1.4034087

Daly, S. R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016b). Comparing Ideation Techniques for Beginning Designers. *Journal of Mechanical Design*, *138*(10), 101108-101108–101112. https://doi.org/10.1115/1.4034087

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design heuristics in engineering concept generation. *Journal of Engineering Education*, *101*(4), 601–629.

Davis, D., Trevisan, M., Leiffer, P., McCormack, J., Beyerlein, S., Javed Khan, M., & Brackin, P. (2013). Reflection and metacognition in engineering practice. In *Kaplan, M., Silver, N., LaVaque-Manty, D., Meizlish, D. (Eds). Using reflection and metacognition to improve student learning: Across the disciplines, across the academy* (pp. 78–103). Routledge.

Deininger, M., Daly, S. R., Lee, J. C., Seifert, C. M., & Sienko, K. H. (2019). Prototyping for context: Exploring stakeholder feedback based on prototype type, stakeholder group and question type. *Research in Engineering Design*, *30*, 453–471. https://doi.org/10.1007/s00163-019-00317-5

Design Justice Network. (2018). *Design Justice Network Principles*. https://designjustice.org/read-the-principles

Dieter, G. E., & Schmidt, L. C. (2012). Problem definition and need identification. In *Engineering Design* (5th ed., pp. 75–115). McGraw-Hill.

Dieter, G. E., & Schmidt, L. C. (2013). *Engineering design* (5th ed.). McGraw-Hill.

Dorst, K. H., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem-solution. *Design Studies*, *22*(5), 425–437.

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

Dumas, J. S., & Redish, J. C. (1999). *A Practical Guide to Usability Testing* (Revised Edition). Intellect Books.

Duquenoy, P., & Thimbleby, H. (1999). Justice and Design. In *Human-Computer Interaction—INTERACT '99* (pp. 281–286). IOS Press.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120.

Dym, C. L., & Little, P. (2004). *Engineering design: A project-based introduction* (Third). John Wiley & Sons.

Edmondson, A. C. (2018). *The Fearless Organization: Creating psychological safety in the workplace for learning, innovation, and growth*. John Wiley & Sons.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review*, *87*(3), 215–251. https://doi.org/10.1037/0033-295X.87.3.215

Faulkner, W. (2000). Dualisms, hierarchies and gender in engineering. *Social Studies of Science*, *30*(5), 759–792.

Felder, R. M. (1988). Creativity in engineering education. *Chemical Engineering Education*, *22*(3), 120–125.

Flower, A., Burns, M. K., & Bottsford-Miller, N. A. (2007). Meta-analysis of disability simulation research. *Remedial and Special Education*, *28*(2), 72–79.

Frank, M. (2000). Engineering systems thinking and systems thinking. *Systems Engineering*, *3*(3).

Freeman, R. E. (2010). *Strategic management: A stakeholder approach*. Cambridge University Press. https:// doi.org/10.1017/CBO9781139192675

Fritz, M. M. C., Rauter, R., Baumgartner, R. J., & Dentchev, N. (2018). A supply chain perspective of stakeholder identification as a tool for responsible policy and decision-making. *Environmental and Science Policy*, *81*, 63–76.

Gambo, I., Asgarli, G., & Taveter, K. (2022). Managing conflicts of stakeholders' emotional goals in requirements engineering: A case study approach. *SSRN*. http://dx.doi.org/10.2139/ssrn.4160010

Garland-Thomson, R. (2011). Misfits: A Feminist Materialist Disability Concept. *Hypatia*, *26*(3), 591–609. https://doi.org/10.1111/j.1527-2001.2011.01206.x

Garland-Thomson, R. (2017). *Extraordinary bodies: Figuring physical disability in American culture and literature*. Columbia University Press.

Goodman, N., Morris, M., & Boston, K. (2017). *Financial inequality: Disability, race, and poverty in America*. National Disability Institute.

Grant, A. (2021). *Think again: The power of knowing what you don't know*. Viking.

Gray, C. M., McKilligan, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2019). Using creative exhaustion to foster idea generation. *International Journal of Technology and Design Education*, *29*(1), 177–195. https://doi.org/10.1007/s10798-017-9435-y

Green, J., Willis, K., Hughes, E., Small, R., Welch, N., Gibbs, L., & Daly, J. (2007). Generating best evidence from qualitative research: The role of data analysis. *Australian and New Zealand Journal of Public Health*, *31*(6), 545–550.

Guilford, J. P. (1950). Creativity. *American Psychologist*, *5*.

Guilford, J. P. (1958, April 1). *Can creativity be developed?* Pacific Arts Association, Asilomar, California.

Hadi, A., & Lande, M. (2019). Understanding the roles of low-fidelity prototypes in engineering design activity. *ASEE Annual Conference & Exposition 2019*.

Halliday, C. S., Paustian-Underdahl, S. C., Stride, C., & Zhang, H. (2022). Retaining women in male-dominated occupations across cultures: The role of supervisor support and psychological safety. *Human Performance*, *35*(3–4), 156–177.

Hamraie, A. (2017). *Building access: Universal design and the politics of disability*. University of Minnesota Press.

Hauser, J. R., & Clausing, D. (1988, May). The house of quality. *Harvard Business Review*. https://hbr.org/1988/05/the-house-of-quality

Hendren, S. (2020). *What Can a Body Do? How We Meet the Built World*. Riverhead Books.

Hernandez, J. (2021, July 17). One of the deadlist U.S. accidental structural collapses happened 40 years ago today. *National Public Radio*. https://www.npr.org/2021/07/17/1016603199/one-of-the-deadliest-u-s-accidental-structural-collapses-happened-40-years-ago-t

Hess, J. L., & Fila, N. D. (2016). The manifestation of empathy within design: Findings from a service-learning course. *CoDesign*, *12*(1–2), 93–111.

Holmes, K. (2018). *Mismatch*. MIT Press.

Hyun Lee, J., & Ostwald, M. J. (2022). The relationship between divergent thinking and ideation in the conceptual design process. *Design Studies*, *79*. https://doi.org/10.1016/j.destud.2022.101089.

IDEO. (2015). *The Field Guide to Human-Centered Design*.

IDEO. (2019). *The Human-Centered Design Toolkit*.

IEEE. (2019). IEEE Strategic Plan 2020-2025. *IEEE: Advancing Technology for Humanity*. https://www.ieee.org/about/ieee-strategic-plan.html

Inclusive Design Research Centre. (n.d.). Philosophy: What is inclusive design? *OCAD University*. Retrieved January 27, 2023, from https://idrc.ocadu.ca/about/philosophy/

Ishikawa, K., & Loftus, J. (1990). *Introduction to quality control* (Vol. 98). 31 Corporation.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Jing, G. G. (2008). Digging for the root cause. *ASQ Six Sigma Forum Magazine*, *7*(3).

Jonassen, D., Strobel, J., & Beng Lee, C. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education*, *95*(2), 139–151.

Kafer, A. (2013). *Feminist, queer, crip*. Indiana University Press.

Karimi, P., Rezwana, J., Siddiqui, S., Maher, M. L., & Dehbozorgi, N. (2020). Creative sketching partner: An analysis of human-AI co-creativity. *25th International Conference on Intelligent User Interfaces*, 221–230. https://doi.org/10.1145/3377325.3377522

Kaur Bagga, S., Gera, S., & Nadimul Haque, S. (2013). The mediating role of organizational culture: Transformational leadership and change management in virtual teams. *Asia Pacific Management Review*, *28*, 120–131.

Kazerounian, K., & Foley, S. (2007). Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions. *Journal of Mechanical Design*, *129*(7), 761–768. https://doi.org/10.1115/1.2739569

Khurana, A., & Rosenthal, S. R. (1998). Towards Holistic "Front Ends" In New Product Development. *Journal of Product Innovation Management*, *15*(1), 57–74. https://doi.org/10.1111/1540-5885.1510057

Kouprie, M., & Visser, F. (2009). A framework for empathy in design: Stepping into and out of the user's life. *Journal of Engineering Design*, *20*(5), 437–448.

Kramer, J., Agogino, A. M., & Roschuni, C. (2016). Characterizing Competencies for Human-Centered Design. *ASME 2016 International Design Engineering Technical Conferences*.

Krumrei-Mancuso, E. J., Haggard, M. C., LaBouff, J. P., & Rowatt, W. C. (2020). Links between intellectual humility and acquiring knowledge. *Journal of Positive Psychology*, *15*(2), 155–170. https://doi.org/10.1080/17439760.2019.1579359

Ku, G., Wang, C. S., & Galinsky, A. D. (2015). The promise and perversity of perspective-taking in organizations. *Research in Organizational Behavior*, *35*, 79–102.

Kudrowitz, B., & Dippo, C. (2013). Getting to the novel ideas: Exploring the alternative uses test of divergent thinking. *ASME 2013 International Design Engineering Technical Conference*.

Kujala, J., Sachs, S., Leinonen, H., Heikkinen, A., & Laude, D. (2022). Stakeholder engagement: Past, present, and future. *Business & Society*, *61*(5), 1136–1196.

Kuppers, P. (2021). *Eco Soma: Pain and Joy in Speculative Performance Encounters*. University of Minnesota Press.

Ladau, E. [@emily_ladau]. (2019, May 19). *Idea for tech students who design stair-climbing wheelchairs: Invent a power wheelchair with a back-up battery to alleviate anxiety [Tweet]*. https://twitter.com/emily_ladau/status/1130124023805952001

Lahdesmaki, M., Siltaoja, M., & Spence, L. (2019). Stakeholder salience for small business: A social proximity perspective. *Journal of Business Ethics*, *158*(2), 375–385. https://doi.org/10.1007/s10551-017-3707-z

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174.

Laut Design. (2023). *Product Design: Great brands make products people love*. https://lautdesign.com/product-design/

Lawanto, O. (2010). Students' metacognition during an engineering design project. *Performance Improvement Quarterly*, *23*(2), 117–136.

Lee, J. W., Daly, S. R., Huang-Saad, A., Rodriguez, G., DeVries, Q., & Seifert, C. M. (2021). A solution in search of problems: A cognitive tool for solution mapping to promote divergent thinking. *Journal of Engineering Design*, *32*(6), 300–321.

Linton, S. (1998). *Claiming Disability: Knowledge and Identity*. NYU Press.

Liston, V. (n.d.). *Behind the Design: OXO's Iconic Good Grips Handles*. Retrieved March 1, 2021, from https://www.oxo.com/blog/behind-the-scenes/behind-design-oxos-iconic-good-grips-handles/

Liu, Y.-C., Bligh, T., & Chakrabarti, A. (2003). Towards an "ideal" approach for concept generation. *Design Studies*, *24*(4), 341–355.

Lopes, D. C., Gerolamo, M. C., Pereira del Prette, Z. A., Musetti, M. A., & Del Prette, A. (2015). Social skills: A key factor for engineering students to develop interpersonal skills. *International Journal of Engineering Education*, *31*(1(B)), 405–413.

Louviere, J. J., Flynn, T. N., & Marley, A. A. J. (2015). *Best-worst scaling: Theory, methods and applications*. Cambridge University Press.

Loweth, R. P., Daly, S. R., Hortop, A., Strehl, E. A., & Sienko, K. H. (2020). An in-depth investigation of student information gathering meetings with stakeholders and domain experts. *International Journal of Technology and Design Education*.

LSA Inclusive Teaching, University of Michigan. (n.d.). *Social Identity Wheel*. Retrieved January 30, 2023, from https://sites.lsa.umich.edu/inclusive-teaching/social-identity-wheel/

Ma, H. H. (2009). The effect size of variables associated with creativity: A meta analysis. *Creativity Research Journal*, *21*(1), 30–42. https://doi.org/10.1080/10400410802633400

Makhlouf, T. E., Murphy, L. R., Daly, S. R., & Seifert, C. M. (2023). *Who is this design for? Promoting consideration of people during concept generation*. ASME 2023 International Design Engineering Technical Conference, Boston, MA.

Marzano, R. J., Brandt, R. S., Hughes, C. S., Jones, B. F., Presseisen, B. Z., Rankin, S. C., & Suhor, C. (1988). *Dimensions of thinking: A framework for curriculum and instruction*. Association for Supervision and Curriculum Development.

McAuliffe, M. (2016). The potential benefits of divergent thinking and metacognitive skills in STEAM learning: A discussion paper. *International Journal of Innovation, Creativity and Change*, *2*(3), 1–13.

McCrae, R. R. (1987). Creativity, divergent thinking, and openness to experience. *Journal of Personality and Social Psychology*, *52*(6), 1258–1265.

McDonagh, D., Denton, H., & Chapman, J. (2009). Design and emotion. *Journal of Engineering Design*, *20*(5), 433–435. https://doi.org/10.1080/09544820902915300

McDonagh-Philip, D., & Bruseberg, A. (2000). Using focus groups to support new product development. *Institution of Engineering Designers Journal*, *26*(5).

McKay, A., Baker, R., Chittenden, R., & de Pennington, A. (2018). *A framework for students to visualise the implications of design decisions in global supply networks*. International Conference on Engineering and Product Design Education, London, UK.

McKay, A., Chittenden, R., Hazlehurst, T., de Pennington, A., Baker, R., & Waller, T. (2022). The derivation and visualization of supply network risk profiles from product architectures. *Systems Engineering*, *25*, 421–442. https://doi.org/10.1002/sys.21622

Miaskiewicz, T., & Kozar, K. A. (2011). Personas and user-centered design: How can personas benefit product design processes? *Design Studies*, *32*(5), 417–430. https://doi.org/10.1016/j.destud.2011.03.003

Michigan Engineering. (2023). Strategic vision: People-first engineering. *University of Michigan*. https://strategicvision.engin.umich.edu/people-first-engineering/

Miles, M. B., Huberman, A. M., & Saldana, J. (2014). *Qualitative Data Analysis: A methods sourcebook* (3rd ed.). SAGE Publications.

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of Management Review*, *22*(4), 853–886.

Mohedas, I., Daly, S. R., Loweth, R. P., Huynh, L., Cravens, G. L., & Sienko, K. H. (2022). The use of recommended interviewing practices by novice engineering designers to elicit information during requirements development. *Design Science*, *8*(16). https://doi.org/10.1017/dsj.2022.4

Mohedas, I., Daly, S. R., Loweth, R. P., & Sienko, K. H. (2023). Changes to stakeholder engagement approaches throughout a capstone engineering design course. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-023-09833-x

Monat, J. P., & Gannon, T. F. (2018). Applying systems thinking to engineering and design. *Systems*, *6*(34). https://doi.org/10.3390/systems6030034

Morris, A. (2022, January 10). At-home coronavirus tests are inaccessible to blind people. *The New York Times*. https://www.nytimes.com/2022/01/10/health/covid-tests-blind-people.html

Mote Jr., C. D., Dowling, D. A., & Zhou, J. (2016). The power of an idea: The international impacts of the Grand Challenges for engineering. *Engineering*, *2*(1), 4–7. http://dx.doi.org/10.1016/J.ENG.2016.01.025

Muller, I., Hussain, W., & Grundy, J. (2022). So who is impacted anyway—A preliminary study of indirect stakeholder identification in practice. *15th International Conference on Cooperative and Human Aspects of Software Engineering*, 36–40. https://doi.org/10.1145/3528579.3529168

Murphy, L. R., Clancy, S. M., Daly, S.R., & Seifert, C. M. (2022, June). Divergent thinking in engineering: Diverse exploration is key to successful project outcomes. *ASEE Annual Conference & Exposition*.

Murphy, L. R., Daly, S. R., Makhlouf, T., Adar, E., Brueckner, S., & Seifert, C. M. (2021, July). Investigating engineering students' consideration of people during concept generation. *2021 ASEE Annual Conference*.

Murphy, L. R., Daly, S. R., & Seifert, C. M. (2022). Idea characteristics arising from individual brainstorming and design heuristics ideation methods. *International Journal of Technology and Design Education*, 1–42. https://doi.org/doi.org/10.1007/s10798-021-09723-0

Murphy, L. R., Daly, S. R., Seifert, C. M., Adar, E., & Brueckner, S. (2020). Considering people: An exploratory investigation of engineering student ideation. *ASEE Annual Conference & Exposition*.

Murphy, L. R., Makhlouf, T., Daly, S. R., & Seifert, C. M. (2023). What do practicing engineers say about stakeholder exploration? Potential pedagogical strategies to support divergent exploration in design. *Collaborations in Student Design Experiences: Cross-Disciplinary, Cross-Institutional, Community, and Industry Partnerships*. Clive L. Dym Mudd Design Workshop, Harvey Mudd College.

Murray, J. K., Studer, J. A., Daly, S. R., McKilligan, S., & Seifert, C. M. (2019). Design by taking perspectives: How engineers explore problems. *Journal of Engineering Education*, *108*(2), 248–275. https://doi.org/10.1002/jee.20263

NASA History Division. (n.d.). *Sputnik and the dawn of the space age*. Retrieved September 8, 2023, from https://history.nasa.gov/sputnik.html

National Academy of Engineering. (2004). *The Engineer of 2020: Visions of Engineering in the New Century*. National Academy of Engineering. http://www.nap.edu/catalog.php?record_id=10999

Niles, S., Contreras, S., Roudbari, S., Kaminsky, J., & Harrison, J. L. (2020). Resisting and assisting engagement with public welfare in engineering education. *Journal of Engineering Education*, *109*, 491–507.

Noland, J., & Phillips, R. (2010). Stakeholder engagement, discourse ethics and strategic management. *International Journal of Management Reviews*. https://doi.org/10.1111/j.1468-2370.2009.00279.x

Norman, D. (2013). *The design of everyday things: Revised and expanded edition*. Basic Books.

Norman, D. A., & Draper, S. W. (1986). *User centered system design: New perspectives on human-computer interaction.* CRC Press.

Nuseibeh, B., & Easterbrook, S. (2000). *Requirements engineering: A roadmap*. 35–46.

Oliver, M. (2013). The social model of disability: Thirty years on. *Disability & Society*, *28*(7), 1024–1026. https://doi.org/10.1080/09687599.2013.818733

Orvell, A., Kross, E., & Gelman, S. A. (2017). How “you” makes meaning. *Science*, *355*, 1299–1302. https://doi.org/10.1126/science.aaj2014

Osborn, A. F. (1957). *Applied imagination: Principles and procedures of creative thinking* (3rd, revised ed.). Charles Scribner’s Sons.

Osborn, A. F. (1963). *Applied imagination: Principles and procedures of creative problem-solving* (3rd Rev Edition). Scribner.

Ozcelik, D., Quevedo-Fernandez, J., Thalen, J., & Terken, J. (2011, June 22). *Engaging users in the early phases of the design process: Attitudes, concerns and challenges from industrial practice*.

Conference on Designing Pleasurable Products and Interfaces, Milano, IT. https://doi.org/10.1145/2347504.2347519

Pacheco, C., & Garcia, I. (2012). A systematic literature review of stakeholder identification methods in requirements elicitation. *The Journal of Systems and Software*, *85*, 2171–2181. http://dx.doi.org/10.1016/j.jss.2012.04.075

Page, J., & Seering, W. (2023). Steps toward development of a comprehensive set-based design process model: A case study. *ASME 2023 International Design Engineering Technical Conference*.

Paton, B., & Dorst, K. (2011). Briefing and reframing: A situated practice. *Design Studies*, *32*(6), 573–587. https://doi.org/10.1016/j.destud.2011.07.002

Patton, M. Q. (2002). *Qualitative evaluation and research methods* (3rd ed.). Thousand). Sage.

Paulus, P. B., & Yang, H.-C. (2000). Idea generation in groups: A basis for creativity in organizations. *Organizational Behavior and Human Decision Processes*, *82*(1), 76–87. https://doi.org/10.1006/obhd.2000.2888

Piepzna-Samarasinha, L. L. (2018). Care Webs: Experiments in creating collective access. In *Care Work: Dreaming Disability Justice*. Arsenal Pulp Press.

Piepzna-Samarasinha, L. L. (2022). *The Future is Disabled: Prophecies, Love Notes and Mourning Songs*. Arsenal Pulp Press.

Rebovich, Jr., G. (2006). Systems thinking for the enterprise: New and emerging perspectives. *IEEE/SMC International Conference on System of Systems Engineering*.

Ritter, S. M., & Mostert, N. (2017). Enhancement of creative thinking skills using a cognitive-based creativity training. *Journal of Cognitive Enhancement*, *1*, 243–253. https://doi.org/10.1007/s41465-016-0002-3

Roberts, C. A., & Lord, S. M. (2020). Making engineering sociotechnical. *IEEE Frontiers in Education Conference*, 1–4.

Rodriguez Serna, L., Nakandala, D., & Bowyer, D. (2022). Stakeholder identification and prioritization: The attribute of dependency. *Journal of Business Research*, *148*, 444–455.

Rodriguez-Calero, I. B., Coulentianos, M. J., Daly, S. R., Burridge, J., & Sienko, K. H. (2020). Prototyping strategies for stakeholder engagement during front-end design: Design practitioners' approaches in the medical device industry. *Design Studies*, *71*.

Rodriguez-Calero, I. B., Daly, S. R., Burleson, G., & Sienko, K. H. (2023). Prototyping strategies to engage stakeholders during early stages of design: A study across three design domains. *Journal of Mechanical Design*, *145*(4).

Rose, T. (2016, January 16). When U.S. air force discovered the flaw of averages. *Toronto Star*. https://www.thestar.com/news/insight/2016/01/16/when-us-air-force-discovered-the-flaw-of-averages.html

Runco, M. A. (1999). Divergent thinking. In *M.A. Runco & S.R. Pritzker (eds). Encyclopedia of creativity* (Vol. 1, pp. 577–582). Academic Press.

Runco, M. A. (2010). Divergent thinking, creativity, and ideation. In *The Cambridge handbook of creativity* (pp. 413–439). Academic Press.

Runco, M. A. (2023). Divergent thinking as creative cognition. In *The Routledge International Handbook of Creative Cognition* (1st ed.). Routledge.

Runco, M. A., & Acar, S. (2019). Divergent thinking. In J.C. Kaufman & R.J Sternber (Eds.), *The Cambridge handbook of creativity* (pp. 224–254). Cambridge University Press.

Ruth, G. (2018). *The global state of the art in engineering education*. Massachusetts Institute of Technology.

Salado, A., & Nilchiani, R. (2013). *Contextual- and behavioral-centric stakeholder identification*. Conference on Systems Engineering Research, Atlanta, GA. https://doi.org/10.1016/j.procs.2013.01.095

Salter, A., & Gann, D. (2003). Sources of ideas for innovation in engineering design. *Research Policy*, *32*(8), 1309–1324. https://doi.org/10.1016/S0048-7333(02)00119-1

Sanders, E. B.-N. (2002). From user-centered to participatory design approaches. In *Design and the social sciences* (pp. 18–25). Taylor & Francis.

Sanders, E. B.-N. (2006). Design Research in 2006. *Design Research Quarterly*, *1*.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*, *4*(1), 5–18. https://doi.org/10.1080/15710880701875068

Sangelkar, S., Vries, C. de, Ashour, O., & Lasher, W. C. (2015). Teaching Idea Generation to Undergraduate Students Within the Time Constraints of a Capstone Course. *2015 ASEE Annual Conference & Exposition*, 26.1476.1-26.1476.14.

Sarkar, P., & Chakrabarti, A. (2007). *Development of a method for assessing design creativity*. International Conference on Engineering Design, Paris, France.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. Basic Books.

Schön, D. A. (1987). *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. Jossey-Bass.

Scott, G., Leritz, L. E., & Mumford, M. D. (2004). The effectiveness of creativity training: A quantitative review. *Creativity Research Journal*, *16*(4), 361–388.

Serrat, O. (2017). The five whys technique. In *Knowledge Solutions*. Springer.

Shah, J. J., Kulkarni, S. V., & Vargas-Hernandez, N. (2000). Evaluation of idea generation methods for conceptual design: Effectiveness metrics and design of experiments. *Journal of Mechanical Design*, *122*(4), 377. https://doi.org/10.1115/1.1315592

Shah, J. J., Smith, S. M., & Vargas-Hernandez, N. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, *24*(2), 111–134. https://doi.org/10.1016/S0142-694X(02)00034-0

Shah, J. J., Smith, S. M., Vargas-Hernandez, N., Gerkens, D. R., & Wulan, M. (2003, September). Empirical studies of design ideation: Alignment of design experiments with lab experiments. *Proceedings of DETC 2003: ASME 2003 International Conference on Design Theory and Methodology*.

Shum, A., Holmes, K., Woolery, K., Price, M., Kim, D., Dvorkina, E., Dietrich-Muller, D., Kile, N., Morris, S., Chou, J., & Malekzadeh, S. (2016). *Inclusive Design Toolkit*. Microsoft Design.

Siebers, T. (2008). *Disability Theory*. University of Michigan Press.

Singh, B., Winkel, D. E., & Selvarajan, T. T. (2013). Managing diversity at work: Does psychological safety hold the key to racial differences in employee performance? *Journal of Occupational and Organizational Psychology*, *86*, 242–263. https://doi.org/10.1111/joop.12015

Singleton, W. T. (1971). Ergonomics and community needs. *Applied Ergonomics*, *2*(1), 37–43. https://doi.org/10.1016/0003-6870(71)90009-3

Sippl, F., Magg, R., Gil, C. P., During, S., & Reinhart, G. (2022). Data-based stakeholder identification in technical change management. *Applied Sciences*, *12*(8205). https://doi.org/ 10.3390/app12168205

Sladovich (Ed), H. E. (1991). *Engineering as a social enterprise*. National Academies Press.

Smith, J., Tran, A. L. H., & Compston, P. (2020). Review of humanitarian action and development engineering education programmes. *European Journal of Engineering Education*, *45*(2), 249–272. https://doi.org/10.1080/03043797.2019.1623179

Smith, R. C., & Iversen, O. S. (2018). Participatory design for sustainable social change. *Design Studies*, *59*, 9–36.

Smith, W. K., Lewis, M. W., & Tushman, M. L. (2016, May). “Both/And” Leadership. *Harvard Business Review*. https://hbr.org/2016/05/both-and-leadership

Smithsonian National Air and Space Museum (Director). (2019, November 4). *The Collapse of “Galloping Gertie” (The Tacoma Narrows Bridge)*. https://www.youtube.com/watch?v=y0xohjV7Avo

Sommerville, I., Rodden, T., Sawyer, P., Bentley, R., & Twidale, M. (1993). Integrating ethnography into the requirements engineering process. *Proceedings of the IEEE International Symposium on Requirements Engineering*, 165–173.

Soriano de Alencar, E. M. L., & de Fatima Bruno-Faria, M. (2011). Characteristics of an organizational environment which stimulate and inhibit creativity. *Journal of Creative Behavior*, *31*(4), 271–281.

Stanford Byers Center for Biodesign. (n.d.). *Biodesign Innovation Process*. Retrieved September 22, 2023, from https://biodesign.stanford.edu/about-us/process.html

Staw, B. M., Sandelands, L. E., & Dutton, J. E. (1981). Threat rigidity effects in organizational behavior: A multilevel analysis. *Administrative Science Quarterly*, *26*(4), 501–524.

Steen, M., de Koning, N., & Pikaart, A. (2004). Exploring human centred approaches in market research and product development—Three case studies. *Proceedings of the Conference on Dutch Directions in HCI*.

Studer, J. A., Daly, S. R., McKilligan, S., & Seifert, C. M. (2018). Evidence of problem exploration in creative designs. *AI EDAM*, *32*(4), 415–430. https://doi.org/10.1017/S0890060418000124

Sun, M., Wang, M., & Wegerif, R. (2020). Effects of divergent thinking training on students' scientific creativity: The impact of individual creative potential and domain knowledge. *Thinking Skills and Creativity*, *37*. https://doi.org/10.1016/j.tsc.2020.100682

Szalma, J. L. (2009). Individual differences in human-technology interaction: Incorporating variation in human characteristics into human factors and ergonomics research and design. *Theoretical Issues in Ergonomics Science*, *10*(5), 381–397. https://doi.org/10.1080/14639220902893613

Treffinger, D., Young, G., Shelby, E., & Shepardson, C. (2002). Assessing creativity: A guide for educators. In *National Research Center on the Gifted and Talented*.

Treviranus, J. (2019, April 21). *Inclusive design: The bell curve, the starburst and the virtuous tornado*. https://medium.com/@jutta.trevira/inclusive-design-the-bell-curve-the-starburst-and-the-virtuous-tornado-6094f797b1bf

Trucchia, V. (2020, September 10). Story of a storyboard. *OpenLab at City Tech*. https://openlab.citytech.cuny.edu/comd1112-fall2020-noriega/2020/09/10/story-of-a-storyboard/

Turner Lee, N., Resnick, P., & Barton, G. (2019). *Algorithmic bias detection and mitigation: Best practices and policies to reduce consumer harms*. The Brookings Institution. https://www.brookings.edu/research/algorithmic-bias-detection-and-mitigation-best-practices-and-policies-to-reduce-consumer-harms/

Ullman, D. G. (2010). *The mechanical design process* (4th ed.). McGraw-Hill.

Ulrich, K., & Eppinger, S. (2015). *Product Design and Development* (6 edition). McGraw-Hill Education.

Valentine, A., Belski, I., Hamilton, M., & Adams, S. (2019). Creativity in electrical engineering degree programs: Where is the content? *IEEE Transactions on Education*, *62*(4), 288–296. https://doi.org/10.1109/TE.2019.2912834

van de Kamp, M.-T., Admiraal, W., van Drie, J., & Rijlaarsdam, G. (2015). Enhancing divergent thinking in visual arts education: Effects of explicit instruction of meta-cognition. *British Journal of Educational Psychology*, *85*, 47–58. https://doi.org/10.1111/bjep.12061

Van den Beemt, A., MacLeod, M., Van der Veen, J., Van de Ven, A., van Baalen, S., Klaassen, R., & Boon, M. (2020). Interdisciplinary engineering education: A review of vision, teaching, and support. *Journal of Engineering Education*, *109*, 508–555. https://doi.org/10.1002/jee.20347

van Lamsweerde, A., Darimont, R., & Letier, E. (1998). Managing conflicts in goal-driven requirements engineering. *IEEE Transactions on Software Engineering*, *24*(11).

van Rijn, H., Sleeswijk Visser, F., Jan Stappers, P., & Deniz Ozakar, A. (2011). Achieving empathy with users: The effects of different sources of information. *CoDesign*, *7*(2), 65–77.

Vincent, A. S., Decker, B. P., & Mumford, M. D. (2002). Divergent thinking, intelligence, and expertise: A test of alternative models. *Creativity Research Journal*, *14*(2), 163–178.

Volkema, R. J. (1983). Problem formulation in planning and design. *Management Science*, *29*(6), 639–652.

Vredenburg, K., Mao, J.-Y., Smith, P. W., & Carey, T. (2002). A survey of user-centered design practice. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, *4*, 471–478.

Walker, B. R., & Jackson, C. J. (2014). How the five-factor model and revised reinforcement sensitivity theory predict divergent thinking. *Personality and Individual Differences*, *57*, 54–58.

Waller, S., Bradley, M., Hosking, I., & Clarkson, P. J. (2015). Making the case for inclusive design. *Applied Ergonomics*, *46*, 297–303.

Walther, J., Miller, S. E., & Sochacka, N. W. (2017). A model of empathy in engineering as a core skill, practice orientation, and professional way of being. *Journal of Engineering Education*, *106*(1), 123–148.

Warren, A., Chege, W., Greene, M., & Berdie, L. (2023). *The financial health of people with disabilities: Key obstacles and opportunities*. Financial Health Network.

Wedell-Wedellsborg, T. (2017). Are you solving the right problem? *Harvard Business Review*. https://hbr.org/2017/01/are-you-solving-the-right-problems

Weiss, R. S. (1994). *Learning from strangers: The art and method of qualitative interview studies*. The Free Press.

Wendell, S. (1996). *The rejected body: Feminist philosphical reflections on disability*. Routledge.

West Virginia Department of Transportation. (2022, December 15). *WVDOT marks 55th anniversary of the Silver Bridge collapse, remembers those who lost their lives*. https://transportation.wv.gov/communications/PressRelease/Pages/WVDOT_marks_55th_anniversary_of_the_Silver_Bridge_collapse_remembers_those_who_lost_their_lives.aspx

Wilson, C. (2006). Brainstorming pitfalls and best practices. *Association for Computing Machinery*, *13*(5), 50–63.

Wobbrock, J. O., Kane, S. K., Gajos, K. Z., Harada, S., & Froehlich, J. (2011). Ability-based design: Concept, principles and examples. *ACM Transactions on Accessible Computing*, *3*(3). https://doi.org/10.1145/1952383.1952384

Wolf, K., & Mieg, H. (2010). Cognitive determinants of the success of inventors: Complex problem solving and deliberate use of divergent and convergent thinking. *European Journal of Cognitive Psychology*, *22*(3), 443–462.

Wong, A. (2020). *Disability Visibility: First-person stories from the twenty-first century*. Vintage Books.

Wonjun, L., Youn-kyung, L., & Richard, S. (2014). Practicing somaesthetics: Exploring its impact on interactive product design ideation. *Proceedings of the 2014 Conference on Designing Interactive Systems*, 1055–1064. https://doi.org/10.1145/2598510.2598561

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2016). Evidence-based design heuristics for idea generation. *Design Studies*, *46*, 95–124. https://doi.org/10.1016/j.destud.2016.05.001

Zampetakis, L. A., Tsironis, L., & Moustakis, V. (2007). Creativity development in engineering education: The case of mind mapping. *Journal of Management Development*, *26*(4). https://doi.org/10.1108/02621710710740110

Zenios, S. G., Makower, J., Yock, P. G., Brinton, T. J., Kumar, U. N., Denend, L., & Krummel, T. M. (2009). *Biodesign: The Process of Innovating Medical Technologies* (1st ed.). Cambridge University Press.

Zhang, T., & Dong, H. (2009, April 8). Human-centred design: An emergent conceptual model. *Include 2009*. Royal College of Art, London. www.hhc.rca.ac.uk/2084/all/1/proceedings.aspx

Zoltowski, C. B., Oakes, W. C., & Cardella, M. E. (2012). Students' ways of experiencing human-centered design. *Journal of Engineering Education*, *101*(1), 28–59.