The Pennsylvania State University

The Graduate School

AN EXPLORATION OF THE IMPACT OF PSYCHOLOGICAL SAFETY IN ENGINEERING DESIGN STUDENT TEAMS

A Dissertation in

Industrial Engineering

by

Courtney Anne Cole

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2022

The dissertation of Courtney Cole was reviewed and approved by the following:

Scarlett R. Miller
Professor of Engineering Design and Industrial Engineering
Dissertation Advisor
Co-Chair of Committee

Kathryn W. Jablokow
Professor of Engineering Design and Mechanical Engineering
Dissertation Co-Advisor
Co-Chair of Committee

Susan Simkins
Professor of Psychology

Jessica Menold
Assistant Professor of Engineering Design and Industrial Engineering

Yiqi Zhang
Assistant Professor of Industrial Engineering

Steven J. Landry
Professor of Industrial Engineering
Head of the Harold and Inge Marcus Department of Industrial and Manufacturing Engineering

ABSTRACT

In the last two decades, psychological safety in teams has grown in importance, and even more so in the last ten years thanks to Google's "Project Aristotle." Specifically, psychological safety is a team construct that describes to what extent the team is safe for interpersonal risk-taking. Psychological safety has been shown to be a consistent, generalizable, and multilevel predictor of outcomes in performance and learning across various fields. While prior work outside of engineering suggests that psychological safety can impact the creative process, particularly in the generation of ideas and in the discussions surrounding idea development, there has been limited investigations of psychological safety in the engineering domain. Without this knowledge, we do not know *when* in the engineering design process fostering psychological safety in a team environment is most important. Furthermore, there is lack of understanding as to what factors within an engineering design team may contribute to lower psychological safety such as surface-level diversity (i.e., gender). Thus, educators in engineering should be concerned about how psychological safety may have an impact on design outputs, as well as how it may be influenced by other traits, such as cognitive style, or an individual's preferred way of coming up with ideas to solve problems (i.e., producing more incrementally or radically different solutions). Additionally, it is important to consider team composition from the perspectives of gender, as some groups may be more at risk for facing adversity that impairs their ability to thrive within their teams. Without an understanding of the role of psychological safety and how it may impact team performance and team dynamics, engineering educators will not be able to devise or assess interventions geared towards the development of psychological safety in teams.

The objective of this dissertation was to identify the impact of psychological safety in engineering design student teams and the factors underlying its establishment. Specifically, this dissertation addressed the following goals: (1) understand how psychological safety impacts the fluency and goodness of design ideas generated, and the underlying role of idea ownership; (2) understand how variations in individual and team deep-level diversity (cognitive style) impact the paradigm-relatedness of ideas from concept generation, prototypes, and the final designs are related, and (3) determine how gender impacts the establishment, building, and maintenance of psychologically safe environments during a multi-week engineering design team project. The results from this research contributes to an understanding of psychological safety in engineering design teams and how to foster it to promote better team performance. The knowledge gained from this dissertation also provides the groundwork for developing future specialized intervention methods to address team issues and to foster psychological safety.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Throughout my doctoral studies, I had the opportunity to be advised and supported by many individuals, to only some of whom I am able to specifically mention here.

First, I would like to thank my advisor, Dr. Scarlett Miller. With your help, I was able to grow as both a researcher and a writer through the past three years I have spent at Penn State. I appreciate your support through our conversations, which helped me to not only grow as an independent researcher, but also prepare for my professional life ahead of me. I would also like to thank Dr. Kathryn Jablokow, as your support in research methodology and life advice helped me to power through conducting my research and writing papers.

I would also like to thank all of the Britelab members, both current and alumni, for their constant support. Thank you to Jessica Gonzalez-Vargas, whose positive mindset was contagious to everyone in our lab and helped me to see things more positively. Thank you to Aoran Peng, whose sense of humor helped me through the rough patches and was always open to having a conversation about our cats. Thank you to Haroula Tzamaras, who I could always turn to for professional and career advice, as well as working through my personal problems. Thank you to Dr. Mohammad Alsager Alzayed and Dr. Rohan Prabhu for all of your advice when I first started the doctoral program, as well as Dr. Hong-En Chen, who helped me with developing my professional documents that led me to be successful in my job search. Thank you to Samantha Scarpinella as well, who helped me with processing the data for the third paper presented in this dissertation. I would also like to thank my undergraduate research assistants, Abby O'Connell, Ava Drum, and Nazifa Prapti for setting up surveys, helping me process raw data, and helping with concept ratings. Without your help, this dissertation would not have been possible.

I would also like to thank my doctoral committee for their expertise and guidance in improving the work in this dissertation. Thank you to Dr. Susan Simkins, whose expertise in organizational psychology helped me with developing appropriate experimental designs and developing meaningful implications from my work. Thank you to Dr. Jessica Menold and Dr. Yiqi Zhang, whose advice helped me to consider other important factors in my work.

If it were not for the support of previous professors at Penn State Behrend that I have had, I would not have been as prepared to pursue an advanced degree. Thank you to Dr. Faisal Aqlan and Dr. Seyed Hamid Reza Sanei for your guidance in my undergraduate research experiences. I would also like to thank Dr. Paul Lynch and Dr. Yuan Huang for their support in helping me navigate my options prior to attending Penn State. Thank you to Dr. Adam Hollinger as well, who was an amazing instructor and role model to me for pursuing advanced studies. I would also like to thank Dr. Atsuki Komiya for giving me the opportunity to work in his heat transfer lab as an exchange student at Tohoku University during my undergraduate studies, which helped to prepare me to work in a lab environment.

To my friends and family, I would not have been able to persevere if it were not for your unwavering support. I would like to thank my friend Dr. Ayasa Tajima, who I met during my first semester in my doctoral studies when she was a postdoctoral scholar at Penn State. From accompanying me in traveling around Pennsylvania to offering moral support, I will always appreciate our friendship. To my parents, Donald and Elizabeth Cole,

thank you for your support and encouragement whenever things became tough for me. I also appreciate you taking care of my late cat, Charlie, while I was away at school and I always looked forward to you sending me pictures of him every day. I would also like to thank my brother, Jake Cole, and my sister-in-law, Jennifer Cole, for their support and encouragement. Also, thank you to my significant other, Randall Doles, for your support in proofreading all of my papers, your MATLAB expertise, helping me with Microsoft Word when my formatting was not being cooperative, and allowing me to bounce ideas off of you. I also thank you for visiting me every other weekend, even though I know the three-hour drive in each direction was not the easiest. I'd also like to thank my previous teachers throughout my life who instilled a profound interest in STEM in me and allowed me to feel more confident in my abilities to pursue a career in engineering. While this list is not exhaustive, I would like to thank my first and third grade teacher, Mrs. Gray (who is also the reason why we had Charlie), my high school physics teacher, Mrs. Harper, and my high school math teachers, the late Mr. Stewart, Mr. Toret, and Mr. Sofran. I would also like to thank the late coworker of my father, Dr. John Swank, who always asked about how I was doing and gave his words of encouragement throughout my doctoral studies.

In addition to my human friends and family, I would like to thank my animal friends in State College, Mr. Foozies, Theodore, and Rory for always greeting me when I would go for a walk. From meowing loudly at me to let him in a stranger's house to following me down the street, I do not think I will ever meet such an interesting and overly friendly cat as Mr. Foozies. Our friendship has enriched my time while in State College, and I know I will miss you when I leave (although I know you will latch onto another passerby).

Finally, I would like to thank and dedicate this dissertation to my late cat, Charlie, who was a friend in many more ways than a human being could ever be. For the past 18 years of my life, you have shown me what true companionship and loyalty is, and I am glad to have had you in my life. From having you as a kitten at the age of seven, I learned so much about how to be responsible and caring, and when to back off and stop pushing your buttons. Even when my brother and I were not there, you brought comfort to my parents and anyone who ever visited. While I remain saddened by your recent passing, I hope you are enjoying chirping at birds and chasing lasers like you loved to, and we will meet again at the Rainbow Bridge. Until then, rest in peace, my little buddy.

This work was funded by the National Science Foundation under Grant No. 1825830. All opinions and findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Charlie (November 7th, 2003—March 28th, 2022) "He was not just a good boy—he was the best boy."

CHAPTER 1

INTRODUCTION

What makes a team most effective? This elusive question is of utmost importance to organizations around the globe [1, 2] due to the widespread belief that teams are more effective at generating solutions to complex problems than individuals alone. Particularly in engineering and engineering design, or the methodological approach used to solve problems that satisfy human needs [3], organizations around the world have integrated teaming as a key aspect of their core business strategy [2, 4]. However, it is unclear as to what characteristics of a team make them most effective. To answer this question, Google's People Operations division spent time trying to uncover what it was about teams in *their* organization that led some to succeed and others to falter [5]. In a project code-named "Project Aristotle" the company explored whether the best teams were made up of people with similar interests or personality attributes, or if team success was more dependent on how often team members socialized or how intelligent the team members were. What they found surprised them; it turned out the *who* part of the equation did not matter. High performance was not dependent on bringing together the most intelligent people. Some "good" teams had "smart" people who figured out how to break up the work evenly, while other "good" teams had "average" people who came up with ways to use each other's strengths to their advantage [6]. Instead, Google's data indicated that *psychological safety*, more than anything else, was critical to making the team work.

Psychological safety is defined as "the shared belief that the team is safe for interpersonal risk taking" ([7] p. 123), and is a seven-question, seven-point survey centered around aspects such as feeling safe to take risks and make mistakes without criticism and feeling valued as a team member [7] (shown in Appendix B). Meta-analytic research has found it to be a consistent, generalizable, and multilevel predictor of outcomes in performance and team learning across fields such as management, organizational behavior, social psychology, and healthcare management [8]. In addition, meta-analytic evidence has also identified a relationship between psychological safety, learning, and performance, showing that this relationship has the greatest impact on tasks which are complex, knowledge-intensive, and involve creativity and sense-making [9]. These are the very descriptors that characterize the engineering design process [10, 11] which can be broken down into three general phases: generation, evaluation (e.g., concept screening and selection), and communication [12-14]. Particularly, the early conceptual stages (i.e., problem formation, concept generation, and concept selection) involve aspects such as risk-taking in teams when sharing ideas during the generation process, and selecting ideas during the selection process [15]. This stems from how concept generation has been taught as encouraging teams to develop creative ideas that are novel and useful [16], but there is no guarantee that students within teams will feel safe to do so. Beyond the early conceptual stages, the prototyping stage that follows concept screening and selection practices can also be impacted by how safe team members feel to take a risk, where students tend to perceive more unique ideas as riskier if the fidelity is lower [17]. This could cause teams to overlook potentially successful ideas if they do not feel safe for risk-taking [7, 8]. This leads into the final stage, where teams compile their work over the course of a project. This stage can be affected by poor communication, which can promote interpersonal tension and irritation [8], and lack of time management [10]. These aspects in the engineering design process are critical aspects of psychological safety as defined by Edmondson [7], motivating the need for research on engineering design under a psychological safety lens.

While psychological safety shows promise as an important aspect of teams to capitalize on in engineering design, little is known about the factors that impact teams' development of psychological safety in this context. For example, conflict in teams can occur at any one of the stages, and where conflict and argumentation may be beneficial for overall performance as team members challenge each other to come up with better solutions [18, 19], leading to a more effective output than had they worked individually. However, prior studies show that high psychological safety is key to using conflict effectively to speak out against potential issues [7, 20, 21], positing that low psychological safety could prevent teams from leveraging the benefits of conflict. However, the connection between psychological safety and interactions such as conflict in engineering design remain unclear, as current work lacks of emphasis on psychological safety in engineering design using Edmondson's inventory. The most common "assessment" of psychological safety in engineering design comes from the Comprehensive Assessment of Team Member Effectiveness (CATME), used widely in engineering education to create teams and assess team performance [22]. However, it only contains themes of psychological safety [23, 24] and has only speculated about the role of psychological safety in undergraduate engineering team student projects [25-27]. Thus, there is a need to thoroughly investigate psychological safety throughout the design stages.

In addition, to establish psychological safety, previous research has shown that *trust*, while different from psychological safety (see Figure 1.1), is a critical component [28]. Without a certain level of trust, low psychological safety can impair the ability to communicate ideas and knowledge as shown in healthcare teams [29] and meta-analytic research with industrial organizations [8]. Additionally, low psychological safety has been shown to impair risk-taking in teams through feeling apprehensive in offering creative solutions [7, 21, 30]. However, team leaders can set the tone to create a psychologically safe environment through building trust with team members [8, 9]. These aspects are important as they help to establish a theory of how psychological safety may impact engineering design via performance outputs. Specifically, the freedom to express creative ideas has been linked to *idea fluency*, or the number of ideas a team develops [31, 32], which could be impacted by psychological safety during concept generation. This is important, as a greater number of ideas could allow teams to explore a wider solution space in terms of originality [33, 34], as well as explore a diverse pool of ideas [35] to select and test later. Additionally, the perceived *idea goodness*, or quality/effectiveness of an idea [36] could be impacted by psychological safety during concept screening due to the metric's reliance on team members' perceptions of an idea. However, these metrics have yet to be explored under a psychological safety lens in engineering design.

Figure 1.1 Infographic on the differences between psychological safety and trust (adapted from Science For Work [37])

In addition to exploring the role of psychological safety on design outputs, it is also important to understand characteristics of the team that may impact this relationship. For example, while prior research has linked psychological safety to creativity by showing that it can help enable individuals to propose unique ideas and promote them to give constructive feedback to teammates [20, 30]; creative outputs can be driven by an individual's cognitive style, or the stable, characteristic cognitive preference that describes how people seek or respond to change [38]. Cognitive style differs from cognitive level, which defines an individual's capacity for engaging in problem-solving and creative behavior [39]. To measure cognitive style, the Kirton Adaptive-Innovation (A-I) theory was developed to quantify the construct [39, 40]. In addition, creative outputs do not simply depend on being creative or not, but rather ideas can be considered on a continuum from incremental to radical, also known as the paradigm-relatedness of an idea [41, 42]. While prior research in engineering design [43] has used the consensual assessment technique

(CAT) to investigate to what extent an idea is creative [44], investigation of the paradigm-relatedness of design outputs can be used to understand to what extent ideas fall on a continuum [42]. Additionally, psychological safety can play a role in whether team members feel safe to act in their typical cognitive style, as individuals in a team may deviate from acting within their typical cognitive style if they feel compelled to adjust to the "norms" of the group [39]. As such, it is important to investigate the relationship between paradigm-relatedness of design outputs from stages such as concept generation, prototyping, and the final deliverables; the second goal of this dissertation.

Beyond the potential impact of cognitive style on design outputs, it is also important to consider whether these diversity characteristics and others may impact the manifestation of psychological safety. Specifically, while not under a psychological safety lens, team composition from the perspective of surface-level diversity such as gender and ethnic background has been shown to have differential effects on team performance and relationship conflict in student teams in business [45]. Additionally, prior research in the production facility context has investigated the impact of racial background on psychological safety, showing that it has a greater impact diversity climate (e.g., perceptions of whether an organization values and integrates diversity [46]) and extra-role behaviors (e.g., behaviors that go above role expectations and promote the organization to function more efficiently [47]) in minority groups [48]. Other studies have also investigated the relationship between gender, showing that gender diversity has a positive impact on psychological safety in industry settings [49, 50]. Particularly, greater gender diversity has been shown to mitigate the negative effects of status conflicts that harm creative outputs [50]. However, specifically how team composition in terms of gender impacts performance outputs, and more importantly how psychological safety is impacted by such composition in the engineering design context remains not understood well. This calls for an investigation of the impacts of such team composition on psychological safety at each stage of the design process. This would allow us to come up with intervention methods to understand how to promote psychological safety in teams of various compositions at various stages of the design process. This is the final goal of this dissertation. The overall relationship of the inputs and outputs utilized in this dissertation is shown in Figure 1.2.

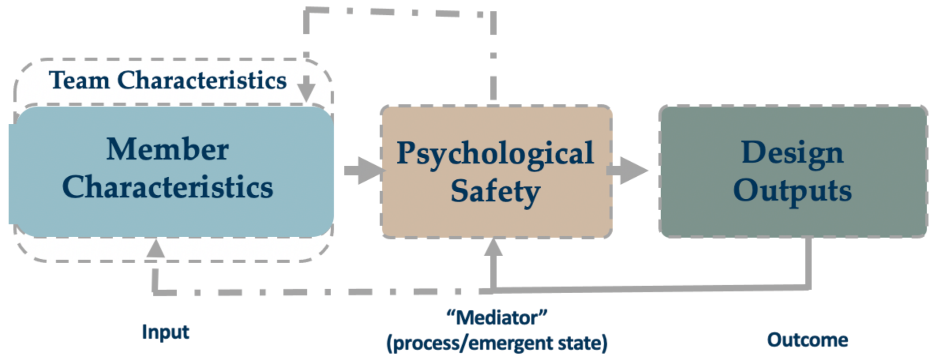


Figure 1.2 General overview of the inputs and outputs of psychological safety

1.1 Dissertation Goals

In light of this prior work, **the current dissertation was developed to explore the impacts of psychological safety on engineering design student teams' design outputs, and the factors underlying its establishment.** Specifically, the goals of this dissertation were to: 1) identify the relationship between team psychological safety and engineering design outputs during concept generation and concept screening in the forms of idea fluency, idea goodness, and ownership bias, 2) understand how variations in individual and team deep-level diversity (cognitive style) impact the paradigm-relatedness of concepts that are generated, selected, and prototyped, and 3) determine how gender impacts the establishment, building, and maintenance of psychologically safe environments during a multi-week engineering design team project. The remainder of this chapter provides a detailed review of prior work on psychological safety in various contexts, how psychological safety may impact design outputs, its potential impact on cognitive style and cognitive gap, and its impact on team composition from the perspective of gender. The three manuscripts that constitute this dissertation are summarized and the main contributions of this work can be found in Appendix C.

1.2 Potential Impact of Psychological Safety Across Various Stages in Engineering Design

In its simplest form, the engineering design process consists of three phases: generation of concepts, evaluation of concepts (e.g., concept screening, selection, and the prototyping stages), and team communication [12-14]. In this dissertation, these phases are broken up into five main time points to represent the engineering design process. Specifically, these are: *Team Formation*, *Concept Generation*, *Concept Screening and Selection*, *Prototyping*, and *Final Deliverables*. How psychological safety may impact each stage and its outputs are discussed in the remainder of this section.

At the *team formation* stage, all teams meet for the first time and team cultures are established. This early engagement is critical to the establishment of psychological safety in a team, but teams research has shown that teams often vary in terms of formation, leadership, culture, norms, accountability and infrastructure [51-54]. Additionally, developing *trust* is a critical component of psychological safety [28, 55]. While not many critical outputs can be extracted from this stage, it can set the tone for each team for the remainder of the project.

From team formation, *concept generation* has been taught as encouraging teams to develop creative ideas that are novel and useful [16]. For example, research in healthcare teams showed that individuals in teams with low psychological safety tended to avoid sharing novel ideas in teams [29], which alludes to a relationship between psychological safety and the outputs at *concept generation*. Establishing whether or not a relationship exists is important because researchers have linked freedom to express creative ideas to the number of ideas, or the *fluency* of ideas, a team develops [31, 32]. This in turn would give teams a more diverse range of ideas to choose from as a potential solution to their design prompts. Specifically, higher psychological safety has been shown to stimulate the production of new products and services through allowing individuals to feel interpersonally safe to share their ideas [56]. Additionally, speaking up and embracing mistakes has been shown to encourage people to suggest unique ideas through decreasing fears of interpersonal risk-taking and increasing creativity and innovation in teams [20, 21, 30]. This also emphasizes the potential role that psychological safety plays during concept generation.

While feeling interpersonally safe to generate novel ideas may help overcome the fear of risk-taking [7, 21, 30], it does not necessarily guarantee that team members can overcome barriers to brainstorming in groups [57]. Some of these barriers are known as "production blocking," where only one person at a time can speak, causing others to miss their chance to share a potentially good idea [57]. This is echoed in prior findings where nominal groups (individuals working by themselves) tended to generate more ideas and more original ideas than their interactive group counterparts [58, 59]. Conversely, "social loafing" may occur in groups when individuals do not feel as accountable in the group for evaluation purposes (such as a project grade) in comparison to an individual evaluation [60]. Therefore, these types of group brainstorming issues can hinder performance if they happen to override high team psychological safety. Another aspect to consider at the *concept generation* stage is that while some literature supports the benefits of generating many ideas in terms of originality [33, 34] and allowing teams to explore a diverse pool of ideas [35], other literature has found that larger quantities of ideas do not necessarily mean that those ideas will be high quality and sometimes the opposite [61, 62], which should be considered when making any claims about psychological safety and ideation.

Proceeding from concept generation, *concept screening* is taught as rating ideas in a go/no-go fashion to expedite the process and avoid wasting time on potentially unsuccessful ideas [63]. Openness to feedback can benefit teams when psychological safety is high, as well as feeling safe for risk-taking when selecting creative ideas [8]. Particularly, higher psychological safety is correlated with a higher level of agreeableness amongst team members [64], which may impact the types of ideas team members screen out during the design process. For example, low levels of psychological safety may impact individuals to be biased towards selecting their own ideas, an effect known as ownership bias [65, 66]. This could impact concept screening due to the relationship between psychological safety, trust, and openness of communication [55], especially when it comes to errors and concerns [28]. Particularly, ownership bias can deteriorate the sense of importance in collaboration [67], which goes against the requirements for high psychological safety [7]. Conversely, the halo effect has been expressed by team members in an engineering design context, where they select their team members' ideas over their own during concept screening to express the "goodness" of an idea [36], as based on a notion of overall quality from [68]. This is because the idea rater perceives that other members produce higher quality designs in comparison to their own designs for the design task [36]. While prior work has demonstrated the effects of ownership bias [69], recent work on an engineering sample identified that ownership bias may only be present when taking into account the "goodness" of the idea [70]. Thus, the relationship between psychological safety and ownership may be mediated by such quality measurements.

Additionally, because "goodness" of an idea is judged by other team members, judgements of idea "goodness" may be affected by psychological safety. This is because prior work has shown that risk aversion can occur when team psychological safety is low [7], and there is a link between team member risk aversion and creative concept generation and selection [15]. The relationship between risk aversion and creativity has been attributed to the fact that creative concepts are considered a high-risk undertaking [70, 71]. Understanding the role of psychological safety during the concept selection process is important because the "availability of creative ideas is a necessary but insufficient condition for innovation" ([59] p. 48) because creative ideas must not only be generated for innovation to occur, but must also be selected throughout the engineering design process.

Upon screening ideas, selection processes serve as a means to further whittle down the number of options to choose from through picking a select few ideas to rate in further detail. For example, some techniques may rely on neural networks [72], whereas others rely on traditional decision matrices or evaluations of creativity [73]. However, all techniques have the same underlying goal of bringing teams closer to selecting the most potentially successful design. When teams navigate the selection process together, the types of ideas that survive can be subject to various team traits. For example, prior work has found that teams with higher levels of conscientious, agreeableness, and tolerance for ambiguity have a greater tendency to select novel concepts [74]. However, how team interactions through the lens of psychological safety could have an even greater effect on what kinds of design outputs survive, as psychological safety plays a role as an antecedent to communication and consequently, decision-making [8]. After the concept screening and selection processes, students engage in *prototyping*, where they try to convey their design [75-78] and detect potential design issues [79]. Prototyping shares some similarities with concept screening and selection processes as well, where prior research shows that engineering design students tend to perceive more unique ideas as riskier if the fidelity is lower [17]. This could cause teams to overlook potentially successful ideas if they do not feel safe for risk-taking [7, 8]. Such notions highlight the importance of investigating how psychological safety could influence how teams carry out these design processes.

Finally, teams compile their work over from the project at the *final deliverables* stage to the class while demonstrating what they have learned. This stage can be affected by poor communication, which can promote interpersonal tension and irritation [8], and lack of time management [10]. In the case of low psychological safety, such issues can fester if team members do not feel safe to question the status quo [7]. Thus, lack of ability to coordinate and come together could be plagued by low psychological safety, emphasizing its importance until the end of a project in ensuring that teams are able to submit all of their deliverables.

As stated before, where psychological safety may not necessarily guarantee positive interactions in groups, higher psychological safety could also elicit some unwanted effects. For example, prior research has found that unethical outcomes in the form of cheating to benefit the whole team are moderated by higher psychological safety [80]. Specifically, such teams have been shown to favor utilitarianism, where some team members spend less time on a task to save time or effort, especially if they are experiencing demands from other classes and want to maintain high grades [80]. Furthermore, feeling comfortable through having higher psychological safety could cause team members to participate in social loafing and "slack off," decreasing average motivation within a team [81]. This form of social loafing could also promote lower fluency, as well as less creativity in teams' outputs [81]. In terms of creative outputs, how psychological safety applies to these and other factors at stake are discussed in the next section.

1.3 Potential Impact of Psychological Safety and Cognitive Style on Creative Design Outputs

While team design outputs at each stage of the engineering design process may be subject to varying levels of psychological safety, other factors that commence at the individual level are important to consider as well. Specifically, to predict the style of outputs with more precision, individuals' cognitive problem-solving processes are important to consider when team members collaborate. Interestingly, research on this topic started to grow nearly 50 years ago when Kirton's Adaption-Innovation (A-I) theory was validated, pointing to *cognitive style* as a factor that can influence the types of ideas and solutions a person generates through that individual's innate cognitive preference for structure [40]. Here, "A-I theory" refers to the theory itself and not the metric that is derived from it. Using A-I theory, an individual's cognitive style falls somewhere within the range of highly adaptive (i.e., strongest preference for structure) to highly innovative (i.e., weakest preference for structure) [39]. In practice, more innovative individuals are less structured thinkers who tend to approach tasks from unsuspected angles, challenge problem constraints, and are more disruptive risk-takers [39, 82]. In contrast, more adaptive individuals are more structured thinkers who refine current systems, focus on precision, reliability, and efficiency, and engage in prudent risk-taking [39, 82]. How this theory grew into a metric that defines cognitive style is discussed in the next section.

1.3.1 Cognitive Style Based on Kirton's Adaptive-Innovative Theory

Cognitive style from the perspective of categorizing individuals as somewhere from adaptive to innovative provides a way to understand how team members of varying characteristics may interact. Since its inception, the influence of Kirton's A-I theory grew from a 32-item inventory (i.e., KAI) that could characterize an individual's preferences for problem-solving [40] to its use in predicting constructs such as online discussion behaviors [83] and creative outputs [84], to name a few. Kirton's A-I theory and the KAI inventory are both built on the key assumption that there are people who prefer "to do things better"

(Adaption) and those who prefer "to do things differently" (Innovation), and are both creative (p. 622) [40]. Varying amounts of adaption and innovation can be beneficial, depending on the problem-solving scenario. In this context, Adaption and Innovation exist on opposite sides of continuous spectrum of *cognitive style*, which is defined as the stable, characteristic cognitive preference that describes how people seek or respond to change [38]. Cognitive style differs from cognitive level, which defines an individual's capacity for engaging in problem-solving and creative behavior [39]. When generating solutions to problems, it is noted that innovators tend filter their ideas less, stretch the problem space boundaries, and rely less on group cohesion, whereas adaptors tend to screen their ideas more carefully, explore thoroughly inside the problem space boundaries, and promote group cohesion [85].

In terms of precise measurement, an individual's KAI score falls somewhere within the range of 32 (highly adaptive) to 160 (highly innovative) [39]. This total score is further broken down into three inter-related sub-scores that correspond to three sub-factors of cognitive style, namely: Sufficiency of Originality (SO), Efficiency (E), and Rule/Group Conformity (R/G) [40]. Specifically, adaptive individuals tend to offer highly detailed ideas that improve upon existing solutions and adhere to the problem definition, whereas innovative individuals tend to offer ideas that challenge the problem statement and solve problems more loosely with less details [38, 39, 86]. Any one of these three sub-factors could impact concept generation; prior research shows that individuals with higher SO and R/G sub-scores tended to perceive their ideas as less diverse when working in a team versus working alone, whereas those with more adaptive SO and R/G sub-scores perceived their ideas as more diverse when working with someone else [85].

1.3.2 Cognitive Gaps in Teams

When individuals of different KAI scores are placed in a team, diversity between individuals' cognitive styles and/or levels increases and the cognitive gaps grow [87]. Here, it is important to make the distinction between cognitive style and cognitive level.

Cognitive style is an individual's stable, characteristic cognitive preference for managing structure in problem-solving, while cognitive level describes an individual's cognitive capacity to solve problems and demonstrate creativity. Cognitive level is assessed through measures of both potential capacity (e.g., intelligence and talent) and manifest capacity (e.g., knowledge and skills) [39]. The just-noticeable difference between individuals' cognitive styles occurs at 10 points on the KAI scale [88, 89]; gaps of 20 points or more can cause conflict in the form of poor communication, blaming one another, and misinterpreting differences in cognitive style as incompetence, for example [87].

Particularly at the team level, this is important because the path to creative results becomes less clear, as there is much debate over *how* to promote team creativity [35, 90] due to the complex dynamics of teams [91-93]. Specifically, when team members' cognitive styles are diverse, cognitive gaps are created. A team can leverage this style diversity by approaching problems using different perspectives, or they can succumb to conflicts that disrupt the team's efforts [39]. Cognitive gaps can be measured in different ways, including the standard deviation of a team's KAI score distribution [94] (referred to as *cognitive style diversity* [95]). Cognitive style can also be measured at the team level through average measures (e.g., a team's average KAI score). Team research shows that computing the average of team members' scores (referred to as *cognitive style elevation* [95]) can be viewed as a collective value that represents the team as a whole [4, 96], as additive aggregation models assume that all team members' scores should be equally represented (e.g., [97]). This gives motivation for examining KAI scores in such a way for a team-level analysis.

Although failing to address such negative interactions could diminish performance, as teams spend more time trying to figure out how to deal with one another, rather than coming up with solutions to the problem itself [39, 98], coping behavior can mitigate these effects [89, 99]. Specifically, coping behavior is a mechanism used by individuals to deal with the negative impacts of cognitive gap by adjusting one's behavior to solve problems in a way that is not consistent with their preferred style [39]. Such effects of coping behavior on actual problem-solving behavior have been expressed in prior literature, where the context (such as class or team) can impact how individuals manipulate their coping behavior [39, 85, 87]. Such behaviors could be further compounded by the task itself, as prior research shows that how a task is proposed can influence the kinds of design solutions that students generate [100, 101]. Additionally, other forms of team communication can also impact how individuals project their behavior, as some individuals may have a greater impact on team outcomes through being dominating or charismatic, or may not say much at all and conform to group norms [102]. To investigate some of these team dynamics, for example, *psychological safety* in the manufacturing context was shown to contribute to the ability to engage in divergent thinking, creativity, and risk-taking [103], alluding to association between divergent thinking and cognitive style. Some studies have even pointed to a connection between trust and the sharing of creative ideas [104], which alludes to a connection to psychological safety, as it is mediated by trust [28, 55]. Such factors are discussed further in the next section.

1.3.3 The Role of Psychological Safety in Managing Team Difficulties

While coping behavior can help individuals of differing cognitive styles modify their own problem-solving behavior to cooperate better within their teams, there are more effective ways to combat team difficulties due to cognitive gap. To mitigate the effects of such interpersonal difficulties beyond coping behavior, psychological safety could serve as a factor that influences how teams resolve or ignore these challenges. For example, throughout the engineering design process, conflict can emerge as resistance to externally imposed task commands and interpersonal conflict within the team atmosphere [12]. Prior work showed that conflict, such the kind that brings upon argumentation, can be beneficial for boosting problem-solving performance [18, 19]. However, conflict is beneficial only if team psychological safety is high, allowing team members to speak out against potential issues in a diplomatic manner and overcome fears of being criticized [7, 20, 21]. Such outcomes of high psychological safety have been shown in both hierarchies of hospital workers [20] and teams learning how to use new medical equipment [105]. Importantly, applications outside of engineering design have shown a connection between psychological safety and employees' feelings of vitality and involvement in creative work [106]. As a result, psychological safety could play a role in creative design practices during the concept generation, selection, and prototyping stages in engineering design process.

1.4 Team Gender Composition in Engineering Design

Through an examination of deep-level diversity such as cognitive style, we can begin to understand how individual factors may impact team-level phenomenon such as psychological safety, and consequently team design outputs. However, this diversity alone may not be enough to understand the intricacies of psychological safety and team output performance. After establishing relationships between psychological safety and various performance outputs in engineering design, it is important to consider team composition as an input to psychological safety to improve psychological safety. While prior work in engineering design looks at team composition from the perspectives of characteristics and cognitive modes [107], and preferences based on personality type [108], for example, it is important to establish a baseline for studying the effects of surface-level diversity on psychological safety. Specifically, surface-level diversity such as gender and ethnic background has been shown to have differential effects on team performance and relationship conflict in student teams in business [45]. On the other hand, research on psychological safety in the team composition of engineering design teams did not consider individual interactions [109], making it difficult to understand how people of varying genders interact with one another. This brings to question the importance of role of team gender composition in psychological safety.

In the context of gender, some studies that focused on engineering teams have found that male dominant teams to tend to engage in more clarifying and standard-setting during team interactions [110], but how this impacts psychological safety lacks emphasis in the engineering design literature. Even more problematic, one study in engineering design indicated an increase in female team members led to lower design performance, but such findings are inconclusive and subjective due to the study's limited understanding for constructing a scale for gender orientation (e.g., the perception of how feminine or masculine something is on a seven-point Likert scale) of a task [111]. In addition to limited findings on gender and design performance, one study observed how gender negatively impacted teams' idea generation practices [112]. Specifically, when gender faultlines are activated with a more feminine or masculine design prompt in mixed-gender teams, design outputs such as idea fluency and overall creativity tended to be lower. Interestingly, qualitative work showed that females pursued engineering as a career to overcome biased designs in society that were more suitable for a male to operate instead of a female [113]. However, many female engineers still face adversity, especially in a workplace setting where they are judged negatively for their gender at first instead of being respected and listened to by males in the first place [114]. Additionally, females in majority-female groups report feeling less anxious than when on minority teams [115], alluding to the notion that females can give other females strength in male-dominated fields such as engineering.

Although these studies leave out psychological safety as a component of what helps or hinders performance in these individuals, such findings point to a discrepancy in how underrepresentation of certain genders in general can lead to frustrations among these groups. Although outside of engineering design, controlling for gender diversity was not found to significantly impact the positive relationship between psychological safety and collective leadership that builds over time, including the beginning of a project [116]. At the individual level, similar findings showed lack of a relationship between individual perceptions of the team's psychological safety and gender at the beginning of data collection [117, 118]. However, how long these team members were working with each other prior to the study, or which team they were in was not explicitly stated. Similarly, investigations in the engineering design context remain limited, as prior work showed only a static view of the impacts of gender [109]. Lack of clarity in how gender can influence psychological safety is problematic, as these studies fail to describe the trajectory of psychological safety over time from the individual (dichotomous ratings) and team levels (team gender composition). Particularly in engineering design, to overcome gender-related issues such as the reluctance to contribute, it is important to identify clearly as to how psychological safety may play a role promoting team members to help individuals and teams share a similar sense of leadership and belonging from the start.

Despite such limited findings in engineering design and related areas, studies on small and medium-sized enterprises showed that there was a significant positive indirect effect of gender diversity on ambidextrous strategic orientation (a form of team performance necessary for sustainable firm performance [119]) mediated by psychological safety [49]. On the other hand, research in R&D teams has shown gender diversity, as defined by Blau's Index for heterogeneity, which ranges from 0 (least diverse) to 0.5 (equal diversity) [120], points to gender diversity as a "double-edged sword" for promoting innovation [121]. Specifically, moderate levels of gender diversity were more likely to share a more positive relationship with innovation, whereas such a relationship with lower or higher gender diversity tended to be less optimal [121]. However, the team dynamics, such as those due to psychological safety, that may have led to such results remain limited in terms of elaboration. Another study also investigated how different factors impact team schema agreement, but gender was not significantly related to this outcome [122], implying that team members do not necessarily share the same schema even if their team composition is predominantly one gender. Beyond shared cognition, prior research has revealed various differences in group communication and leadership emergence between same- and different genders [123] and the kinds of questions that are asked by different genders [124], which can impact team interactions. In terms of knowledge sharing; an output of psychological safety [7, 8], prior work has also shown that females tend to require a more positive social interaction culture than males before they feel safe to engage in knowledge sharing [125]. Finally, research on various company workers recruited via MTurk has shown that the negative effects of status conflict on psychological safety (as based on a scale by [126]) can be mitigated by gender diversity, as well team leaders' perspectives of team creativity [50]. However, it is unclear if the MTurk workers taking the survey were all part of the same team, or rather gave individual perceptions of psychological safety. Additionally, the same study found that there was an indirect relationship between status conflict and team creativity via team psychological safety in business team, but perceptions of team creativity were only taken from the team leaders

[50]. This calls for a more thorough investigation of understanding how gender influences the psychological safety that can influence to engineering design team performance in education.

While there is a lack of understanding of how gender can influence engineering design teams' psychological safety in education, prior work has identified some other factors that may further contribute to individual perceptions of psychological safety. Specifically, qualitative evidence has shown that being both female and multi-minority can complicate how welcome such individuals feel in engineering, especially when interacting with other non-minority individuals [127, 128]. Interestingly, both White and minority women have indicated experience with microaggressions from non-minority individuals in engineering education, where the effects were especially elevated for minority women [129]. While racial background is not a specific focus of this dissertation due to the difficulty in obtaining the same size, these findings can help to understand other factors that may further compound effects felt by minority gender members. As a whole, understanding the connection between team composition and psychological safety can help establish a means of promoting increases in psychological safety with the goal of improving engineering outputs.

1.5 Design Solution Rating Techniques

While team composition from the perspective of gender may have an impact on psychological safety in engineering design teams, it is also important to consider deep-level diversity and its potential connections to design outputs. Specifically, to identify whether deep-level diversity in the form of underlying individual and team cognitive characteristics, such as cognitive style, impacts the creation of paradigm-shifting ideas, how to measure paradigm shifting ideas must be identified. While there is a wealth of creativity measurements available, here the is focus on two different design rating methods: The Consensual Assessment Technique [44, 130] and Paradigm-Relatedness [41, 42].

1.5.1 Consensual Assessment Technique

One of the most widely used, albeit imperfect, methods for measuring design creativity is the Consensual Assessment Technique (CAT) [44, 130]. The underlying premise behind the CAT is that something is creative to the extent to which experts in the field agree, independently, that it is creative [44]. Additionally, to ensure high interrater reliability, it is standard practice to complete a practice set of ratings, and then the raters work independently to rate their assigned ideas separately. While the CAT is supported by over 30 years of research and is used extensively in the social science community [131], it also requires that raters be experts or quasi-experts (novice idea raters) in the domain [44, 130]. Specifically, quasi-expert raters must be trained by experts [132], which can be difficult when evaluating a large number of ideas across various domains. Issues with CAT are further complicated when observed from a global assessment of creativity (see [133, 134]), as a recent study showed lack of significant agreement on global ratings of creativity by experts [131]. This issue is further complicated with novice raters, as interrater reliability is typically lower [44, 135], and research has shown low correlation between the ratings of experts and novices [136]. Another issue that can occur is that the CAT can yield a negative relationship with other idea rating techniques for novelty, such as the Shah, Vargas-Hernandez, and Smith (SVS) method [131]. This implies that CAT does not necessarily yield results similar to other creativity rating schemes. Finally, and perhaps most problematically, this technique of rating creativity dismisses some ideas as "not creative," which directly contradicts A-I theory and limits the interpretation and use of KAI scores to predict the paradigm-relatedness of solutions.

1.5.2 Paradigm-Relatedness of Design Outputs

In the last few years, the engineering community has made significant strides towards developing new rating methods that allow us to consider ideas on a continuum from incremental to radical [42]. Specifically, foundational research first defined *paradigm-relatedness* as a measure of an idea's creative style, "independent of and orthogonal to the creativity level" [137] (p. 89). Years later, the *paradigm-relatedness* creativity rating technique was developed within an engineering design context to evaluate design ideas [41, 42]. Specifically, a *paradigm* refers to the "ways of perceiving or acting in response to a situation or problem," (p. 31), whereas *relatedness* refers to "the extent that an idea operates within" (p. 31) or challenges that paradigm [42]. The metric was taken further by defining categories of *paradigm-relatedness* based on the elements, relationships, and focus of a design concept [138]. Although it can be more difficult to achieve high interrater-reliability when breaking up paradigm-relatedness into components such as *elements*, *relationships*, *constraints*, and *focus* [42], a *category-based* (which involves separating ideas into one of a few broad categories) metric approach is still recommended for assessing large sets of ideas, because it is faster to apply and more reliable [42].

The first category used in this technique, *paradigm-consistent*, describes a solution that resembles an already existing, common design that stays within the problem constraints. The second category, *paradigm-challenging*, either integrates an uncommon element or relationship into the solution and begins to stretch the problem boundaries. The third and final category, *paradigm-breaking*, shifts the focus of the problem to a larger problem while violating some or all relevant constraints [42]. Examples of these are shown in. It is important to note that no one category is better than any other; while some people mistakenly associate only radical ideas with higher levels of creativity [139], incremental ideas are creative as well [84, 140]. The distinction between these types of ideas is important in considering different types of creativity as identifying such differences allows us to generate a variety of ideas that more fully explore the problem space [141, 142]. Unlike those using the CAT, raters using the paradigm-relatedness technique are primed with the problem definition and where it will be used to achieve acceptable levels of interrater reliability [41, 42]. Specifically, when using just a category-based approach, this can make it easier to rate larger quantities of ideas with higher interrater reliability [42]. Although it remains to be investigated for its relationship with KAI scores, the foundation of the paradigm-relatedness rating technique was based on concepts derived from A-I theory [41]. Additionally, despite prior team research using KAI and the assessment of design solutions, the impact of cognitive style on the paradigm-relatedness of design outcomes remains unclear and largely uninvestigated. Understanding this impact is important, because the diversity of strategy and approach in generating both incremental and radical ideas within a team can help teams explore a wider solution space, and thus increase the potential for a successful design [87]. Figure 1.3 shows an example of rated concepts for the practice design task from the crowdsourced study [143] that was a precursor to the study in Chapter 4, where the concepts correspond to the following design task: Design a device that allows people to contact one another.

Smartphone (paradigm-consistent) | Paper airplane with message inside (paradigm-challenging) | Bird carries pre-recorded message (paradigm-breaking)

Figure 1.3 Example of the paradigm-relatedness rating scheme applied to concepts based on the task: Design a device that allows people to contact one another

1.6 Summary of Areas for Investigation

Previous research has focused on psychological safety primarily on healthcare, with some studies focusing on business contexts in both industry and education. Furthermore, the vast majority of studies focused on evaluating psychological safety at a single time point. Similarly, the few studies in engineering design education looked at psychological safety from a single time point, failing to address how psychological safety can be different at any one point in the design process. Furthermore, these studies lack any insight on design outputs, demonstrating the need to adopt a longitudinal view of psychological safety and whether or not it is actually impactful on performance in an engineering design education context and worthwhile to pursue further. Therefore, this dissertation aimed to address these research gaps through demonstrating the relationship between psychological safety and engineering design outputs at the concept generation and screening stages. From there, how the paradigm-relatedness of individuals' and teams' concepts at the concept generation, concept selection, and prototyping stages can be predicted under both psychological safety and cognitive style were investigated. After establishing these relationships, team gender composition was investigated in a longitudinal study to understand how this antecedent can influence psychological safety over time, as well as through dichotomous perceptions of psychological safety at the end of the project. The need to investigate research gaps served as the main objectives of this dissertation and are investigated through three manuscripts, which are summarized in the following section.

1.7 Summary of Dissertation Papers

The scope of this dissertation is restricted to the role of psychological safety in engineering design teams in education. The following subsections serve to provide a brief overview of the three journal articles presented in this dissertation.

Paper I: What is the Relationship Between Psychological Safety and Team Productivity and Effectiveness During Concept Development? An Exploration in Engineering Design Education

The first goal of this dissertation was to explore the role of psychological safety in concept generation and screening practices in engineering design teams in education. Specifically, Paper I in Chapter 2 presents a journal paper published in the Journal of Mechanical Design conducted with 69 engineering design teams across 11 sections of a first-year engineering design cornerstone course. During the study, engineering design students generated and screened concepts, which occurred at two different time points in the engineering design process. Normalized idea fluency was calculated using the average number of ideas generated per team member during the concept generation stage. From there, idea goodness values (or the perception of the overall quality or effectiveness of an idea, developed by Toh and Miller [36]) were obtained from concept screening sheets, which were then used to calculate incidences of ownership bias when idea authors selected their own ideas with low idea goodness. Results suggest that feeling psychologically safe may make team members feel comfortable to not have to produce as many ideas as other teams within their team. It was also shown that increased psychological safety shares a relationship with a higher average idea goodness of all team members' ideas, indicating a potential relationship between having trust in others' ideas and increases in psychological safety. However, incidences of ownership bias could not be detected via psychological safety. These findings provide evidence of psychological safety's importance in engineering design outputs. A summary of input and output variables for this study is shown in Figure 1.4.

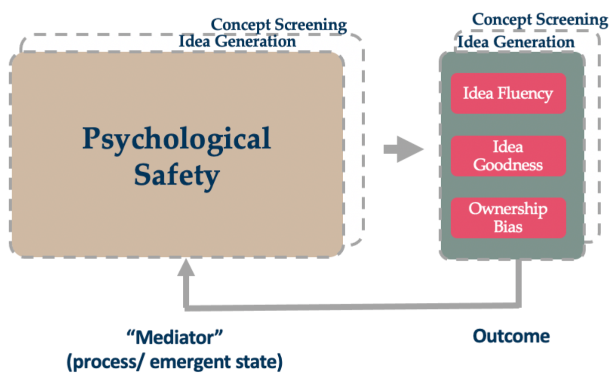


Figure 1.4 Visualization of psychological safety as an input to concept generation and screening process outputs in Paper I

Paper II: An Exploration of the Relationships Between Cognitive Style, Psychological Safety, and the Paradigm-Relatedness of Design Solutions in Engineering Design Teams in Education

The second goal of this dissertation was to identify how psychological safety, coupled with cognitive style (i.e., an individual's preferred way of problem-solving [40]) played a role in predicting the likelihood of design outputs to be categorized within certain paradigms. Specifically, Paper II in Chapter 3 presents a journal paper submitted to the Journal of Mechanical Design conducted with the same 69 engineering design teams across 11 sections of a first-year engineering design cornerstone course from Paper I. The data from this study was collected from students' design sessions, where 1,450 individual concepts from concept generation were collected and rated using the paradigm-relatedness metric developed by Silk et al. [41]. From there, 73 additional concepts that were team-generated and selected by the team to be prototyped were rated as well. Finally, the 69 concepts of each functional prototype for each team were gathered and rated using the same paradigm-relatedness metric. The paradigm-relatedness metric was simplified as three categories for rating: (1) paradigm-consistent; where concepts are in line with typical expected solutions, (2) paradigm-challenging; where concepts contain some expected and not-so-expected elements, and (3) paradigm-breaking; where concepts solve the problem using unexpected elements and break constraints.

After using two quasi-experts to rate all concepts according to this scheme, the first multi-level analysis on individual concept generation design outputs showed that controlling for design task was a significant predictor of the paradigm-relatedness of individuals' concepts. However, neither individual perceptions of psychological safety nor cognitive style were significant predictors for predicting the likelihood of individual concepts being categorized as specific paradigm-relatedness categories. Similarly, team-level analyses showed that neither psychological safety nor cognitive style diversity (i.e., the spread of a team's cognitive style scores), and controlling for cognitive style elevation (i.e., the average cognitive style score of a team) were not significant predictors for predicting the percentage of selected concepts that fall into each of the three paradigm-relatedness categories. However, controlling for the availability of concepts via the entire percentage of concepts in each of the paradigm-relatedness categories was significant. This implied that the availability of certain kinds of concepts based on their paradigm can predict how the few concepts that survive are of a certain paradigm. Finally, results from prototyping showed that cognitive style diversity could significantly predict the likelihood of the paradigm-relatedness of the functional prototype concepts. This meant that as cognitive style diversity increased, the more likely a team would be to produce a functional prototype that is either paradigm-challenging or paradigm-breaking when comparing to the reference category, paradigm-consistent. Overall, these results show the limited role that psychological safety played in predicting the paradigm-relatedness of design outputs, even though there were significant findings in Paper I. Thus, this study established future directions for investigating other confounding variables. A summary of input and output variables for this study is shown in Figure 1.5.

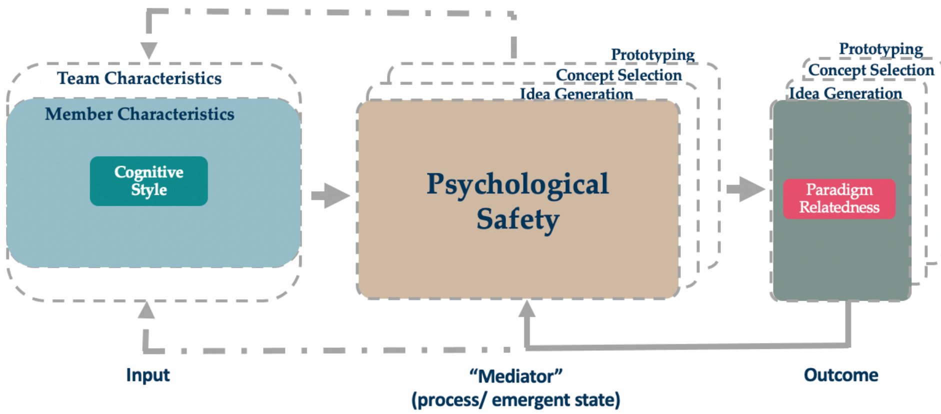


Figure 1.5 Visualization of psychological safety as an input to the paradigm-relatedness of design outputs at various stages in Paper II

Paper III: The Impact of Gender on Individual Perceptions and Team Psychological Safety in Engineering Design Teams

The final goal of this dissertation was to investigate gender's role as an input to psychological safety, establishing a baseline for investigating other inputs to the psychological safety that could impact design outputs. Specifically, Paper III in Chapter 4 of this dissertation presents a manuscript to be submitted to the Journal of Mechanical Design, which focused on dichotomous perceptions of psychological safety from the perspective of gender, as well as the impacts of team gender composition on team psychological safety. The data was collected from a different set of students from that of what was presented in Papers I and II, where 38 engineering design teams made up of 121 males and 27 females participated in this study across 6 sections of a first-year engineering design cornerstone course. After engaging in five time points in the engineering design process in an 8-week project, individuals within their teams were instructed to not only fill out the psychological safety survey at each of the time points, but they also rated their perceptions of how psychologically safe they were with each member on their team. The analysis showed that while accounting for nesting within teams, females felt less psychologically safe with males than they did other females within their teams, and females felt less psychologically safe with males than males did with females. Furthermore, analyses at the team-level showed that while team gender composition from the perspective of 19 gender homogeneous (all male) teams did not differ in psychological safety scores in comparison to 19 gender heterogeneous teams (mixed gender). However, psychological safety was significantly higher at the final deliverables stage in comparison to the first two stages, team formation and concept generation. These results emphasize that while team analyses were not significant, individual analyses showed alarming results, meaning that psychological safety is still an issue for minority gender groups such as females. The results from this study lay the groundwork for analyzing other inputs to psychological safety, as well as demonstrate the need to analyze the effects of gender in more detail at the team level. A summary of input and output variables for this study is shown in Figure 1.6.

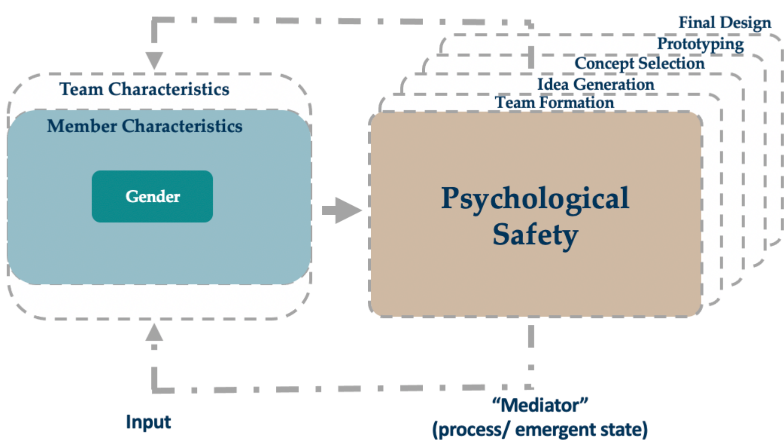


Figure 1.6 Visualization of gender as an input to psychological safety various stages in Paper III

1.8 Contributions

This dissertation develops a theoretical understanding of the role of psychological safety in engineering design teams in education. Specifically, the results of this dissertation contribute to engineering design studies in the following ways. First, this dissertation provides evidence to support psychological safety's importance in engineering design outputs during concept generation and concept screening practices. This dissertation identified that psychological safety shared an inverse relationship with idea fluency, whereas psychological safety shared a positive relationship with idea goodness. However, psychological safety could not be used to detect incidences of ownership bias. Second, this dissertation identifies the limited impact of individual and team measures of psychological safety and cognitive style on the paradigm-relatedness of design outputs. In fact, psychological safety was not a significant predictor of design outputs gathered from individual concept generation, as well as team concept selection and functional prototyping practices. However, cognitive style diversity significantly predicted that as this diversity increased, so did the likelihood for teams to select more paradigm-challenging and paradigm-breaking concepts to prototype as the functional prototype over paradigm-consistent concepts. Finally, this dissertation identifies the significant role of individual dichotomous perceptions of psychological safety, where females felt less psychologically safe in general, but differences in psychological safety were not as apparent from the team composition perspective. As a whole, this dissertation presents several implications for addressing issues with engineering design teams from the perspective of psychological safety. Furthermore, it establishes the groundwork for future work to build a greater understanding of psychological safety in these teams.

1.9 Document Outline

To address the research objectives in this dissertation, a total of four chapters are included in this document to present a literature review and a methodology of the studies performed as part of this dissertation. Specifically, Chapter 2 presents the first journal article of this dissertation, which focuses on the relationship between psychological safety and concept generation and screening outputs. Chapter 3 presents the second journal article of this dissertation and focuses on the role of psychological safety and cognitive style in the paradigm-relatedness of design outputs. Chapter 4 presents the third journal article of this dissertation on focuses on the role of gender as an input to psychological safety. Chapter 5 provides a summary of the findings of this research and highlights the contributions and the implications of this work for engineering design education.

CHAPTER 2

WHAT IS THE RELATIONSHIP BETWEEN PSYCHOLOGICAL SAFETY AND TEAM PRODUCTIVITY AND EFFECTIVENESS DURING CONCEPT DEVELOPMENT? AN EXPLORATION IN ENGINEERING DESIGN EDUCATION

This paper has been submitted for publication in the Journal of Mechanical Design in October 2021. This work is multiple-authored by Courtney Cole, Jacqueline Marhefka, Dr. Kathryn Jablokow, Dr. Susan Simkins, Dr. Sarah Ritter, and Dr. Scarlett Miller. Courtney Cole is the lead author on the paper, and Dr. Scarlett Miller and Dr. Kathryn Jablokow helped advise the work.

2.1 Abstract

While psychological safety has been shown to be a consistent, generalizable, and multilevel predictor of outcomes in team performance across fields that can positively impact the creative process, there have been limited investigations of psychological safety in the engineering domain. Without this knowledge, we do not know whether fostering psychological safety in a team environment is important for specific engineering design outputs from concept generation and screening practices. This study provides one of the first attempts at addressing this research gap through an empirical study with 69 engineering design student teams over the course of 4- and 8-week design projects. Specifically, we sought to identify the role of psychological safety on the number and quality (judged by goodness) of ideas generated. In addition, we explored the role of

psychological safety on ownership bias and goodness in the concept screening process. The results of the study identified that while psychological safety was negatively related to the number of ideas a team developed, it was positively related to the quality (goodness) of the ideas developed. This result indicates that while psychological safety may not increase team productivity in terms of the number of ideas produced, it may impact team effectiveness in coming up with viable candidate ideas to move forward in the design process. In addition, there was no relationship between psychological safety and ownership bias during concept screening. These findings provide quantitative evidence on the role of psychological safety on engineering team idea production and identify areas for further study.

2.2 Introduction

What makes an engineering design team most effective? This elusive question is of utmost importance to organizations around the globe [1, 2] due to the widespread belief that teams are more effective at generating solutions to complex problems than individuals alone. This increased team performance has been attributed to the range of knowledge and experience held by the team [3, 4]. While engineering organizations around the world integrate teaming as a key aspect of their core business strategy [2, 3], it is unclear what characteristics make a team productive.

To answer this question, Google's People Operations division spent time trying to uncover what it was about teams in *their* organization that led some to succeed and others to falter [4]. In a project code-named "Project Aristotle," the company explored whether the best teams were people with similar attributes, or if team success was more dependent on how often team members socialized or their intelligence. Surprisingly, the *who* part of the equation didn't matter. High performance was not dependent on bringing together the most intelligent people. Some "good" teams had "smart" people who figured out how to break up the work evenly, while other "good" teams had "average" people who came up with ways to use each other's strengths to their advantage [5]. Specifically, Google's data indicated that *psychological safety* was critical to making the team successful.

Psychological safety, or "the shared belief that the team is safe for interpersonal risk taking" ([6] p. 123), has been found to be a consistent, generalizable, and multilevel predictor of outcomes in performance and learning across fields such as management, organizational behavior, social psychology, and healthcare management [7]. Additionally, meta-analytic evidence identified a relationship between psychological safety, learning, and performance, showing that this relationship has the greatest impact on tasks which are *complex*, *knowledge-intensive*, and involve *creativity* and *sense-making* [8]. This is the very description of the skills needed in the *engineering design process* [9, 10]. Particularly, facets of the psychological safety construct could relate to engineering design outputs, where feeling valued by one's team, or feeling safe to take a risk and not fearing criticism for making mistakes [6] could drive the innovativeness and riskiness of the ideas that team members propose and select. Regardless, there is still limited evidence on the impact of psychological safety on engineering outputs.

While psychological safety has not been heavily explored in engineering, research in innovation management has provided evidence on why it may be an important area to explore. Specifically, research in this field has linked psychological safety to creativity by showing that it can help enable individuals to propose unique ideas and promote them to give constructive feedback to teammates [11, 12]; an important set of skills in engineering education [13]. These results indicate a possible relationship between psychological safety and team performance during the *concept generation and screening* stages of the engineering design process. Interestingly, the Comprehensive Assessment of Team Member Effectiveness (CATME), used widely in engineering education to create teams and assess team performance [14], contains themes of psychological safety [15, 16]. However, research on this tool has only speculated about the role of psychological safety in undergraduate engineering team student projects [17-19]. Finally, while our own prior work has validated the longitudinal reliability of psychological safety in an engineering student sample [9], there have been limited investigations into the effectiveness or use of this measure on engineering team outputs.

In light of this prior work, the goal of the current paper was to explore the role of psychological safety on team productivity and effectiveness during the conceptual phases of the engineering design process. It is important to mention that while some studies look at the "innovation process" to promote team design outputs [20], our work focuses specifically on a psychological safety lens. The results of this study provide empirical evidence of the role of psychological safety in engineering design teams' productivity. These results can be used to understand *to what extent* psychological safety shares a relationship with design outputs, and to establish whether building upon existing interventions focused on psychological safety [21] may be worthwhile to pursue for fostering team psychological safety in engineering.

2.3 Related Work

In its simplest form, the engineering design process consists of three phases: generation, evaluation (e.g., concept screening), and communication [22-24]. During *concept generation,* teams seek to develop creative ideas, or those that are both novel and useful [25]. On the other hand, *concept screening* involves rating ideas in a go/no go fashion in an effort to evaluate new ideas quickly and prevent committing resources to potentially unsuccessful ideas [26].

2.3.1 Occurrences of Team Issues Throughout the Engineering Design Process

In the midst of these stages, conflict can seep into the team atmosphere, where resistance to externally imposed task demands and interpersonal conflict can occur [22]. Specifically, when people of varying cognitive styles (i.e., an individual's cognitive preference for solving problems [27, 28]) and cognitive levels (i.e., an individual's cognitive capacity for to solve problems and display creative processes [28]), a cognitive gap between team members can occur [28, 29]. While cognitive gap can help diverse team members explore the solution space, it can also incite conflict if team members' differences are not managed [28, 29]. While some studies have shown that conflict holds value, such as engaging in problem-solving through argumentation [30, 31], prior work has also shown that such conflict is only beneficial if the psychological safety of the team is high, allowing members to tactfully challenge issues [6, 11]. For example, low levels of psychological safety hindered performance of employees in manufacturing companies, causing individuals to feel a "lack of growth" and "not be heard" as they struggle to improve the product [32]. In addition, research in hierarchies of hospital workers communicating through intense, unpredictable contexts [11], as well as cardiac departments trying to learn new technologies [33], has shown that when team psychological safety is high, members are more prone to speak out against problems and dismiss fears of being criticized for making mistakes [6, 34]. This safety has been shown to be built upon emotional interactions and deep conversations within a team that convey to team members how individuals want to portray themselves and how others make them feel [5]. To understand these interactions better, analysis of audio recordings can help to break down verbal communication into meaningful bits of information [35], as understanding teams' trends in psychological safety can be difficult without this context.

While outside the context of engineering, research has also linked psychological safety to employees' feelings of vitalities and ultimately their involvement in creative work [36]. This is critical to consider, as techniques such as the Consensual Assessment Technique (CAT) [37] has been used in engineering design to rate the creativity [38-40]; a critical design criterion in engineering design [41]. Recent work has also looked at examining ideas as incremental to radical changes to the existing solution [42, 43], which show promise as a technique for examining design outputs [44]. Although an investigation of creative outputs and/or radical ideas is not within the scope of this paper, investigating the broader outputs helps to establish the direction of how teams may perform. Specifically, prior studies show a connection between psychological safety and creativity such that individuals are more likely to propose unique ideas and engage in the process of giving constructive feedback within the team [11, 12]. Similarly, another study showed that healthcare teams with low psychological safety tended to avoid sharing creative ideas [45], whereas prior work in manufacturing showed that psychological safety contributed to divergent thinking, creativity, and risk-taking [46]. However, the ability to produce creative outputs does not come without a cost, as the team's ability to explore the solution space can come from the aforementioned cognitive gap, which could also be detrimental to team performance if interpersonal issues due to the gap are not resolved [28, 29]. In addition to this gap, design task can also impact how team members produce design outputs [47], as well as background knowledge on the task itself [48], either limiting or promoting performance from specific individuals.

2.3.2 Potential Impact of Psychological Safety on Engineering Design Outputs

In addition to this empirical work, reviews of the psychological safety literature have identified several promising areas for research, including adopting a dynamic view of psychological safety to understand how the construct is established, builds, wanes, and/or disappears completely over time [7, 8]. This is important in the context of engineering, because a lack of psychological safety in a team environment may manifest itself differently throughout the design process [9]. For example, prior work in healthcare showed that teams with low psychological safety refrained from sharing novel ideas with each other [45]. This finding suggests a potential relationship between psychological safety and *concept generation* in the engineering design process. Establishing whether or not this relationship exists is important because researchers have linked freedom to express creative ideas to the number of ideas, or the fluency of ideas [49, 50]. In some cases, high psychological safety may stimulate the production of new products and services through feeling interpersonally safe to share their ideas [51]. Additionally, speaking up and embracing mistakes may encourage people to suggest unique ideas through, effectively increasing creativity and innovation in teams [11, 12, 34]. However, while feeling interpersonally safe to generate novel ideas may help overcome the fear of risk-taking [6, 12, 34], it does not necessarily guarantee that team members can overcome barriers to brainstorming in groups such as "production blocking," where only one person at a time can speak [52]. This is echoed in prior findings where nominal groups (individuals working by themselves) tended to generate more ideas and more original ideas than their interactive group counterparts [53, 54]. Conversely, "social loafing" may occur in groups when individuals do not feel as accountable in the group for evaluation purposes (such as a project grade) in comparison to an individual evaluation [55]. Therefore, these types of brainstorming issues may hinder performance if they happen to override high team psychological safety. Another aspect to consider at the *concept generation* stage is that while some literature supports the benefits of generating many ideas in terms of originality [56, 57] and allowing teams to explore a diverse pool of ideas [58], other literature has found that larger quantities of ideas do not necessarily mean that those ideas will be high quality and sometimes the opposite [59, 60], which should be considered when making any claims about psychological safety and ideation. In other words, idea production (more ideas) does not necessarily equal idea effectiveness (producing the right ideas).

Psychological safety may also play an important role in the *concept screening* stage of the engineering design process. In fact, it is thought that high psychological safety is correlated with a high level of agreeableness amongst team members [61], which may impact the types of ideas team members screen out during the design process. For example, low levels of psychological safety may impact individuals to be biased towards selecting their own ideas, an effect known as ownership bias [62, 63]. This could impact concept screening due to the relationship between psychological safety, trust (not the same as psychological safety, but can serve as an input [7]), and openness of communication [64], especially when it comes to errors and concerns [65]. In particular, ownership bias can deteriorate the sense of importance in collaboration through enticing individuals to choose their ideas over others' ideas [66], potentially impacting selection processes that can impact the final design [67]. This is problematic because lack of collaboration goes against the requirements for high psychological safety [6]. Conversely, the halo effect has been expressed by team members in an engineering design context, where they select their team members' ideas over their own during concept screening to express the "goodness" of an idea [68], as based on a notion of overall quality from [69]. This is because the idea rater perceives that other members produce higher quality designs in comparison to their own designs for the design task [68]. While prior work has demonstrated the effects of ownership bias [66], recent work on an engineering sample identified that ownership bias may only be present when taking into account the "goodness," a measure of design quality, of the idea [70]. Thus, the relationship between psychological safety and ownership may be mediated by such quality measurements. However, how interactions outside the classroom occur could confound with the in-class building and waning of psychological safety that may contribute to design outputs, as students may use technology to communicate (e.g., texting/instant messaging applications and social networking systems) to work on assignments and/or study together [71]).

While findings from these aforementioned studies provide the foundation for why psychological safety may impact engineering design outputs, there has been limited evidence on its role in the productivity and effectiveness of concept development tasks such as those present in engineering design. The current study was developed to fill this void.

2.3.3 Research Questions

The main goal of the current paper was to explore the role of psychological safety on engineering team performance in the conceptual phases of the design process. Specifically, the following research questions (RQ) were explored:

> *RQ1: What is the relationship between psychological safety and the fluency and goodness of the ideas that teams develop during concept generation?*
>
> > Our hypothesis was that as psychological safety increases, the total number of ideas (fluency) created per team would increase, as would the average idea goodness rating per team. This is important during concept generation, as a greater number of ideas per team could present a diverse pool of designs to choose from [58], allowing teams to explore the solution space.

Specifically, psychological safety has been shown to facilitate the contribution of ideas [7] and encourage people to take initiative to develop new products and services [51]. Furthermore, because idea goodness is judged by team members, it may be a way of showing that a team member has more trust from the perspective of team members generating viable ideas, which can influence the psychological safety of teams positively [65] as well as promote agreeableness within the team [61].

RQ2: What is the relationship between psychological safety and team performance during concept screening?

Our hypothesis was that as psychological safety decreases, the incidence of ownership bias at the team level would increase. Particularly, ownership bias is linked to performance through representing teams' lack of collaboration via members within teams that overlook others' potentially successful ideas [66]. Because ownership bias is most noticeable when team members are given the option to either select their ideas or others' ideas, we decided to investigate this phenomenon during *concept screening*. Furthermore, we proposed that a decrease in perceptions of psychological safety at the individual level would also cause ownership bias to increase among individuals. This is because ownership bias is related to team members having a preference for their own ideas [68, 70], causing them to lose sight of the importance of collaboration. In relation to idea goodness, an increased selection of one's own ideas that are rated low by others can be construed as a sign that ownership bias is existent [70].

2.4 Methodology

To answer the research questions presented above, we conducted an empirical study at a large northeastern university over the first project of a cornerstone engineering design course from semester during Summer 2018 to Spring 2020. Figure 2.1 depicts the study timeline. These time points were chosen because they represent milestones in the engineering design process for a team [22], and we can extract performance outputs as a result of team interaction for analysis. Further details of the study design are presented in the remainder of this section.

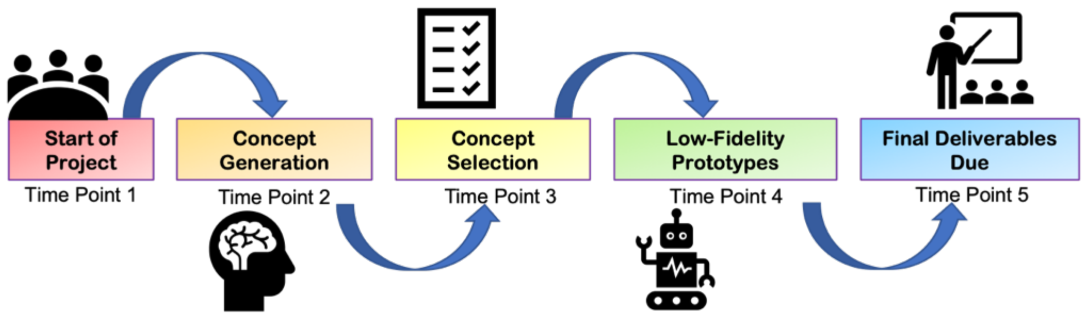


Figure 2.1 Study timeline – Psychological safety was captured at the end of each time point (total time period: 8 weeks for Fall/Spring, and 4 weeks for Summer)

2.4.1 Participants

Sixty-nine engineering design student teams, comprised of 263 participants (188 males and 75 females), participated in the study. All participants were enrolled in a first-year engineering design course at a large northeastern university. The study was integrated into the curriculum and the students were graded based on their participation.

2.4.2 Procedure

The study was completed over the course of two years with a first-year cornerstone engineering design class. Specifically, eleven sections of this course were studied in the current investigation; seven of which took part over the course of a typical semester (15 weeks) while four transpired over a condensed summer session (6 weeks) (see Table 2.1 for the summary). The same course schedule was followed and adhered to, and the psychological safety of the teams was analyzed over the same five time points in all

Table 2.1 Descriptions of design challenges based on instructor and semester

Semester	Instructor	Sample Size (n)	Project Description
Summer 2018	A	46 students; 12 teams	Tackle food insecurity in developing countries as a result of climate, conflict, unstable markets, food waste, and lack of investment in agriculture.
Spring 2019	A and B	49 students; 13 teams	Ensure healthy lives and promote the well-being for all at all ages through addressing diseases, pollution, and traffic injuries.
Summer 2019	A	48 students; 12 teams	Ensure healthy lives and promote the well-being for all at all ages through addressing diseases, pollution, and traffic injuries.
Fall 2019	A	32 students; 8 teams	Ensure healthy lives and promote the well-being for all at all ages through addressing diseases, pollution, and traffic injuries.
Fall 2019	C	30 students; 8 teams	Develop a new water toy for children ages 3 to 5 to teach STEM in a fun, safe, novel way.
Spring 2020	A and D	58 students; 16 teams	Ensure healthy lives and promote the well-being for all at all ages through addressing diseases, pollution, and traffic injuries.

instantiations of the course (see Figure 2.1). Each design session at their respective time point lasted approximately 1 hour and 50-minutes in every semester, making the time to complete each activity roughly equal in length. At the end of each time point, students completed an electronically delivered seven-question psychological safety survey developed by Edmondson [6], shown in Appendix B. These survey questions center around the degree to which team members feel comfortable making mistakes without criticism, bringing up difficult issues intended to help the group, and feeling accepted and valued as a team member [6]; all of which are important for providing feedback in an engineering team [13]. A popular example of one of these questions is, "If you make a mistake on this team, it is often held against you" [6]. Importantly, this investigation focused mainly on concept generation and screening (Time Points 2 and 3), however, it is important to state the previous stages that lead into generation and screening practices, and what outputs come out of these stages that feed into later design stages. All participants consented at the beginning of the study based on the Institutional Review Board guidelines established at the university. The remainder of this section highlights what happened for each section of this course at each time point with respect to the current study.

At ***Time Point 1***, 3- and 4-person teams were formed using the 32-item Kirton's Adaption-Innovation (KAI) inventory (validated across the general population and engineers) to determine their cognitive styles [27, 28]. Specifically, although not discussed in the current study, half of the teams were constructed to be homogeneous (all KAI scores within a 10-point range) while the other half were constructed to be heterogeneous by team KAI score. Next, students were presented with a design challenge which differed by term/ instructor of the course (see Table 2.1 for descriptions). The teams then conducted in-depth context research on their design problem, which served as their area of focus for their design project. At the end of the class, the students completed the first psychological safety survey.

During Time Point 2, students attended a lecture on customer needs and developed their problem statements. After this, an innovation module that focused on the importance of creativity in engineering design was then completed. Next, the participants were guided through a series of idea generation exercises where they were asked to individually sketch as many ideas as possible in a 15-minute session in nominal groups. At the end of this period, the instructor collected the ideas which were scanned for analysis. After this, participants completed the second psychological safety survey.

Who's Idea is it?	Idea #	Brief Description of Idea	Is this idea worth considering for further design?	
			Consider	Do Not Consider
Erika	1	Plastic sheet with grid	✓	
Erika	2	Snap off UTI test strips		✓
Derrick	4	Filter across river stream	☐	☒
	1	50gal. drum water storage filter	☒	☐
	3	Mineral filtration system	☒	☐
	2	Portable cap filter for bottles	☒	☐

Figure 2.2 Example of the concept screening sheet for each team member

During Time Point 3, participants were led through a concept selection activity where they individually assessed all of the ideas generated by their design team. Specifically, students were provided the ideas their team generated in Time Point 2 in a random order and asked to individually assess all of the ideas generated by their design team by categorizing the ideas using a concept screening sheet into "Consider" or "Do Not Consider" categories (see Figure 2.2 for an example of the concept scoring sheet). Ideas in the "Consider" category were concepts that the participant felt would most likely satisfy the needs for the problem statement for the course project while ideas in the "Do Not Consider" category were concepts that the participants felt were not adequate in satisfying the design goals. This was continued until all ideas from the group were assessed. The students then discussed the ideas they screened and formed two piles as a group – "Consider" and "Do Not Consider." They were tasked with picking out four distinct ideas to prototype in the next design session. At the end of this time point, the third psychological safety survey was completed.

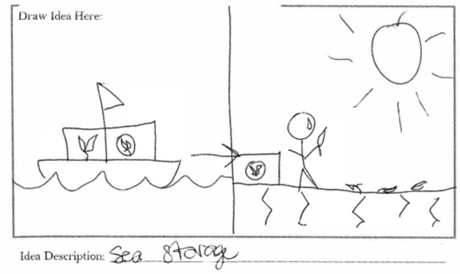
At Time Point 4, students were tasked with developing low-fidelity prototypes of the idea they selected during Time Point 3 using commonly available materials (e.g., foam core, cardstock, post-its, etc.). From there, students were given a few minutes to develop their "elevator pitch" to promote their prototype. Then, the students divided off into eight new teams for 15 minutes to share their elevator pitch and receive feedback on their idea. At the end of this session, all participating students completed the fourth psychological safety survey.

The project ended at Time Point 5, in which the final deliverables were completed including a formal PowerPoint presentation, a final design report, and a high-fidelity prototype including a CAD rendering of the design. After all groups presented their presentations, students were completed the fifth and final psychological safety survey.

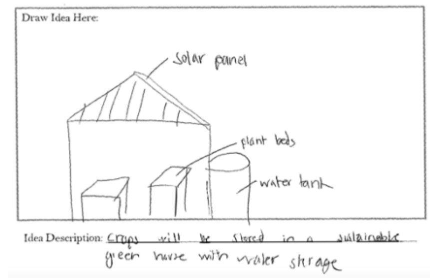
Table 2.2 Examples of ideas generated with goodness scores for each design problem

Food Insecurities

Goodness Score: 0.33

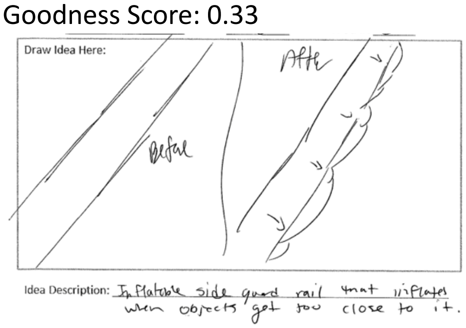


Goodness Score: 1.0

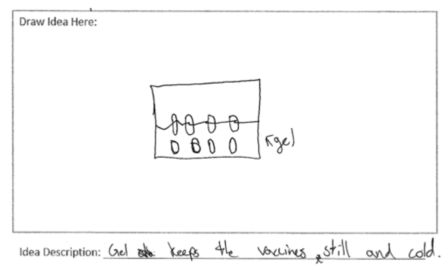


Healthy Living

Goodness Score: 0.33

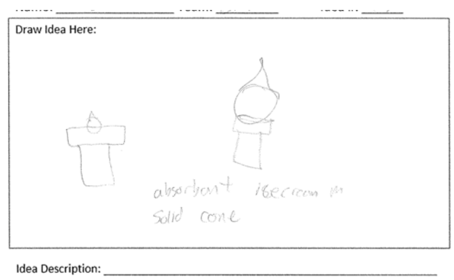


Goodness Score: 1.0

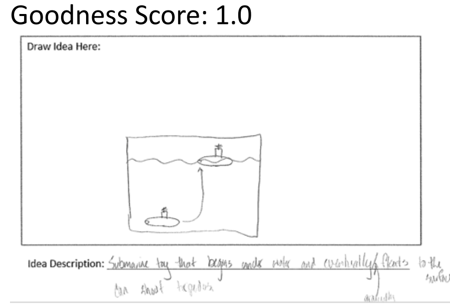


Novel Water Toy

Goodness Score: 0.0



Goodness Score: 1.0



2.4.3 Metrics

To answer the research questions, several metrics were utilized including: Idea fluency, idea goodness, ownership bias, and psychological safety. Each metric is defined in detail in the remainder of this section.

Idea Fluency: Idea fluency [50] is defined as the number of ideas generated. For the current study, this was aggregated at the team level by summing the total number of ideas generated by each team member in **Time Point 2**, concept generation. This measure was then normalized by dividing the number of members on the team because some teams had three members and some had four members. Specifically, it was calculated as follows:

$$idea\ fluency\ per\ team = \frac{\sum_{i=1}^{K} X_{i,j}}{K} \quad (1)$$

where $X_{i,j}$ represents the total number of ideas for team j created by the *i*th participant, with up to *K* participants on team *j*. To calculate this, a custom MATLAB code was developed.

Individual Perceptions of Idea Goodness: Idea goodness was developed by Toh et al. [68] to rate the *overall* quality or effectiveness of an idea (based on metrics from [69]) by aggregating the opinions of team members. As opposed to a scoring method that relies on expert raters that are typically more knowledgeable [37], we use this metric to investigate the decision processes of individuals within a team and whose ideas they are more likely to select. In other words, we want to investigate whether the team leans toward picking others' ideas within the team, or if people within the team pick their own idea as a result of the team psychological safety. An example of ideas with various idea goodness scores is shown in Table 2.2. To compute this metric, data was gathered on what ideas should be considered or not considered on concept screening sheets completed individually by team members during **Time Point 3**, concept screening. Specifically, the calculation for idea goodness is:

$$goodness_{pmn} = \frac{\sum_{m=1}^{M} X_{m,n}}{M} \quad (2)$$

where $X_{m,n} = 1$ if the *m*th team member in team *p* selected the *n*th idea generated by another member in the team for further consideration, and $X_{m,n} = 0$ otherwise [68]. In this equation, a score of 0.5 or higher indicates that a majority of the members agreed to move forward with the idea, whereas a score below 0.5 indicates that minority of members agreed to move forward with the idea. To calculate this, a custom MATLAB code was developed.

Ownership Bias: Ownership bias describes a participant's preference or bias for their own ideas during the design process [70]. To measure ownership bias, the continuous parameter idea goodness was applied to six distinct metrics to analyze the continuous parameter of percentage of ideas selected by the idea generator themselves, or by other team members on both a high level (not considering the idea goodness, but purely the percentage selected), or finer level (ideas designated as "low" or "good" by the team members who did not create the idea). Thus, several metrics were developed and calculated as follows:

percentage of own ideas selected

$$P_{own,selected,i} = \frac{w_i}{t_i} \times 100\% \quad (3)$$

where w_i represents the number of ideas generated by the ith participant that were selected as "consider" by participant i, and t_i represents the total number of ideas that participant i generated.

percentage of own ideas with goodness score above 0.5 selected

$$P_{own,good,selected,i} = \frac{a_i}{x_i} \times 100\% \quad (4)$$

where a_i represents the number of ideas generated by the ith participant that were selected as "consider" by participant i and had a goodness score as determined by their team, and x_i represents the total number of ideas that participant i generated with goodness scores above 0.5.

percentage of own ideas with goodness score equal to or below 0.5 selected

$$P_{own,low,selected,i} = \frac{b_i}{y_i} \times 100\% \quad (5)$$

where b_i represents the number of ideas generated by the ith participant that were selected as "consider" by participant i and had a goodness score as determined by their team, and y_i represents the total number of ideas that participant i generated with goodness scores equal to or below 0.5.

percentage of team members' ideas selected

$$P_{other,selected,i} = \frac{r_i}{s_i} \times 100\% \quad (6)$$

where r_i represents the number of ideas generated by the ith participant's team members that were selected as "consider" by participant i's team, and s_i represents the total number of ideas that participant i's team generated.

2.5 Results

During the study, 3 teams were removed from the Spring 2020 semester due to the teams being broken up part of the way through the semester, invalidating their results. For the analysis at Time Point 2, two of the teams were removed due to issues with team members either not turning in all ideas or only one person responding to the psychological safety survey. This left 67 engineering design teams that generated an average of 6.58 (SD=2.11) ideas per person, where the average psychological safety score was 6.03 (SD=0.505). Furthermore, due to issues with team members not evaluating all ideas from their other teammates, two teams were removed from the idea goodness and ownership bias analyses at Time Point 3. This left 67 teams that selected an average of 68.30% (SD=11.03) of the ideas generated by their respective team members, where the average psychological safety score was 6.11 (SD=0.497). To ensure that the formation of teams via cognitive style did not confound the results presented in the research questions, a hierarchical regression was conducted. We conducted two hierarchical regressions with two steps each. The first hierarchical regression predicted psychological safety at Time Point 2, where KAI (homogeneous or heterogeneous team) was entered as a control variable in the first step, and idea fluency was entered in the subsequent step. The second hierarchical regression predicted psychological safety at Time Point 3, where KAI was entered as a control variable in the first step, and idea goodness and the six cases for ownership bias were entered in the subsequent step. Prior to conducing a hierarchical multiple regression, the relevant assumptions of this statistical analysis were tested. The assumption of singularity was also met as the independent variables (team idea fluency, mean team idea goodness, and each of the six metrics used in ownership bias) were not a combination of other independent variables. From there, an examination of the Mahalanobis distance scores indicated no multivariate outliers. Residual and scatterplots indicated the assumptions of normality, linearity and homoscedasticity were all satisfied. In the case of Time Point 2, controlling for KAI was found to be statistically insignificant, with adjusted $R^2 = -.013$, and $F(1, 66) = .120$, $p = .730$. In the case of Time Point 3, controlling for KAI was found to be statistically insignificant, with adjusted $R^2 = -.015$, and $F(1, 63) = .077$, $p = .782$. The remainder of this section presents the results in reference to our research questions. The statistical data were analyzed via the SPSS v.26. A value of $p < .05$ was used to define statistical significance [72].

2.5.1 RQ1: What is the relationship between psychological safety and the fluency and goodness of ideas teams develop during concept generation?

The goal of our first research question was to identify if a relationship existed between psychological safety and engineering team outputs during the concept generation process. Specifically, we hypothesized that as team psychological safety increased, the total normalized number of ideas (fluency) per team would increase because prior work conducted outside of engineering has shown that psychological safety facilitates the contribution of ideas [7] and new products and services [51]. Furthermore, because idea goodness may tap into feelings of trust within the team and influence an increase in psychological safety [65] and also increase agreeableness within the team [61], we also hypothesized that as psychological safety increases, the average idea goodness would also increase.

Prior to the analysis, the validity of team aggregations of psychological safety at Time Point 2 was verified because psychological safety is a team level construct. This was achieved through interrater agreement calculations. The results revealed an acceptable level of agreement and thus the construct was considered valid at this time point (r_{wg} = 0.88, ICC(1) = 0.178, ICC(2)=0.431) [73]. This is based on the criteria defined in LeBreton and Senter (2008) [73], where our ICC(1) estimates are medium effects (around ICC(1)=.10 is considered as such) and the r_{wg} values indicate strong agreement (r_{wg} between .71 and .90 is considered as such). In addition, statistical assumptions were checked prior to the analysis. Specifically, requirements for homoscedasticity were met, as assessed by visual inspection of a plot of standardized residuals versus standardized predicted values. In addition, normality was confirmed by visually inspecting the histograms and Q-Q plots.

Once assumptions were validated, two linear regression analyses were conducted. The first linear regression used the independent variable of psychological safety during Time Point 2, concept generation, and the dependent variable idea fluency. One outlier (15 ideas per participant with a psychological safety score of 6.95) was present in the data, which was transformed into the next highest value (11.67 ideas per participant), as leaving the outlier would result in a different statistical conclusion. The results of the regression analysis significantly predicted a relationship between these variables, $F(1, 65) = 5.752$, $p = .019$. Specifically, psychological safety accounted for 6.8% of the explained variance in idea fluency; a small effect size according to Cohen [74]. The regression equation was: predicted normalized idea fluency = 12.98 – 1.073x (psychological safety). A scatterplot of this is shown in Figure 2.3. This finding did not support our hypothesis; psychological safety was shown to facilitate the contribution of ideas in a negative manner; the opposite of what prior research pointed towards [7]. Although these results were surprising at first, we analyzed the data even further to understand why psychological safety was inversely related with normalized idea fluency. Specifically, a multivariate linear regression analysis was conducted with the dependent variables being the standard deviation of team idea fluency, the maximum idea fluency within a team, the minimum idea fluency within a team, the minimum idea goodness within a team (where the idea goodness scores were averaged for each participant to indicate the average quality of a person's ideas), and the standard deviation of team idea goodness. The independent variable was psychological safety at Time Point 2.

Our results from the multivariate linear regression revealed that while the standard deviation of idea fluency (R^2=-.015, p=.882), maximum idea fluency (R^2=.010, p = .199), minimum idea goodness within a team (R^2=.039, p=.06), and the standard deviation of team idea goodness (R^2=.005, p=.248) were not significantly related to psychological safety at Time Point 2, minimum idea fluency was significantly related. Further analysis via a regression analysis significantly predicted a relationship between these variables, F(1, 65) = 4.596, p = .017. Specifically, psychological safety accounted for 7.0% of the explained variance in idea fluency; a small effect size according to Cohen [74]. The regression equation was: predicted minimum idea fluency = 10.075 – .888x (psychological safety). A scatterplot of this is shown in Figure 2.4. This result helped to explain the inverse relationship between psychological safety and normalized idea fluency in the main analysis, as teams tended to have at least one team member exhibit signs of social loafing, even when the team's psychological safety increased in comparison to teams with low psychological safety (usually around a score of 4 for this study). The individual may not have felt the need to contribute as much, lowering average team motivation [75]. This can be seen as an unintended effect of high psychological safety, similar to what has been found in previous literature [75, 76]. To explain the findings of our results even further, we performed a linear regression that used the independent variable normalized idea fluency, and the dependent variable mean team idea goodness. While the results of the regression analysis failed to significantly predict a relationship between these variables, F(1, 64) = 3.770, p = .057, we were able to see a trend beginning to form based on the equation: predicted idea goodness = .393 - .048x (normalized idea fluency). Regardless, the results did not meet criteria for statistical significance, indicating no relationship. However, because prior work found that idea quantity does not necessarily equal quality [59, 60], future work may benefit from a larger sample size.

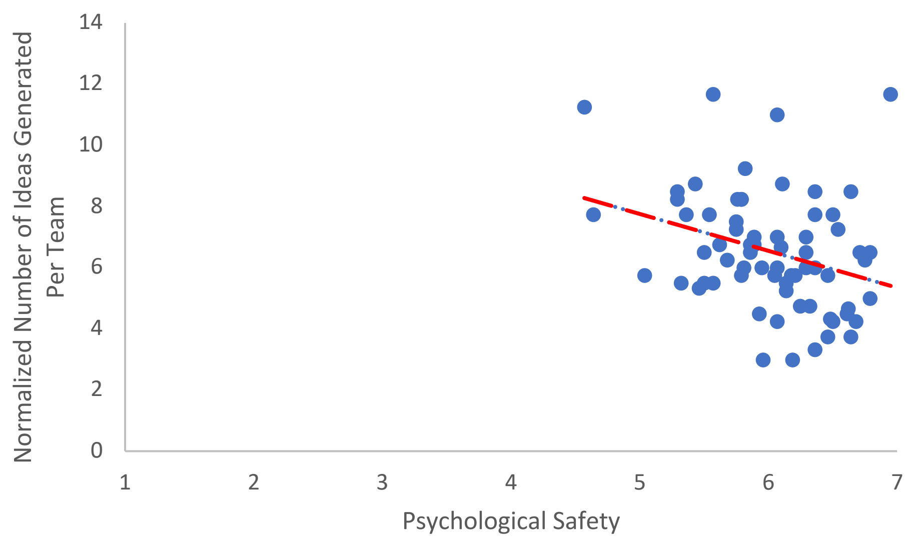


Figure 2.3 The normalized idea fluency of each team as a function of psychological safety (PS) at Time Point 2, $F(1,65) = 5.752$, $p = .019$

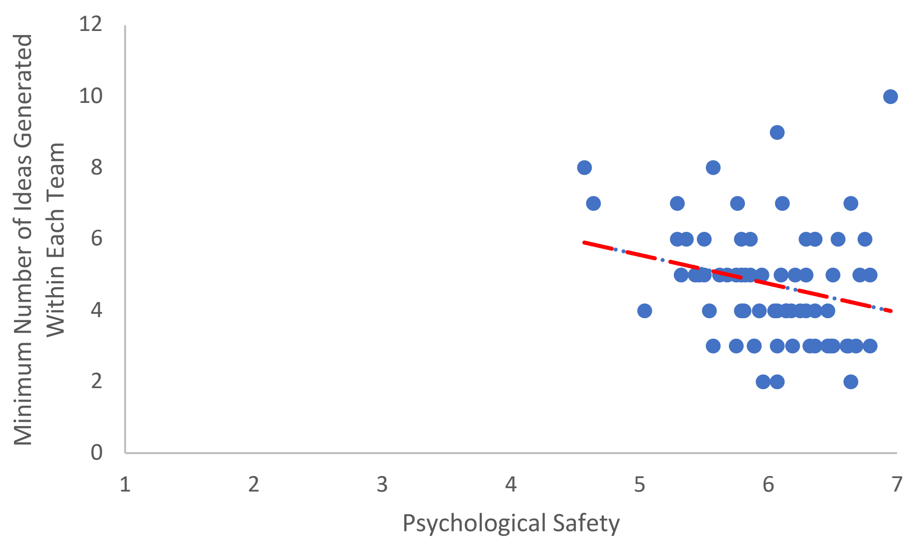


Figure 2.4 The minimum idea fluency of within each team as a function of psychological safety (PS) at Time Point 2, $F(1,65) = 4.596$, $p = .017$

The second linear regression had the independent variable of psychological safety during Time Point 3, and the dependent variable idea goodness. The results of the regression analysis identified that psychological safety significantly predicted idea goodness, $F(1, 65) = 4.937$, $p < .05$. Specifically, psychological safety accounted for 7.1% of the explained variance in idea goodness. The regression equation was: predicted idea goodness = 0.32 + 0.059x (psychological safety). A scatterplot of this is shown in Figure 2.5. This finding supported our hypothesis such that team psychological safety would promote higher levels of team idea goodness, based on the notion that higher psychological safety is associated with agreeableness amongst team members [61].

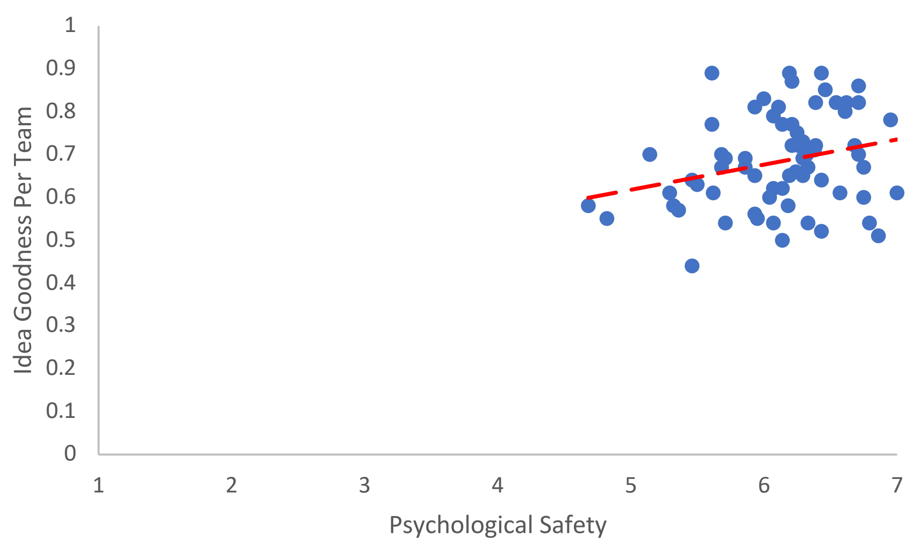


Figure 2.5 Average team idea goodness as a function of psychological safety (PS) at Time Point 3, $F(1,65) = 4.937$, $p < .05$

Although psychological safety was found to be associated with the total number of ideas generated per team in a negative manner, it was associated with more viable ideas. This result indicates that as psychological safety increased, so did the average idea goodness of the team. Because psychological safety impacts the team's likelihood to take risks [6], rating others' ideas highly could be a form of "risk-taking." This implies that team members are comfortable enough that they are willing to try more of their team members' ideas. This can also be alluded to trust being an important factor in psychological safety [34], where high trust in team members' abilities can promote risk-taking in the form of selecting others' ideas.

2.5.2 RQ2: What is the relationship between psychological safety and team performance during concept screening?

The goal of our second research question was to examine if a relationship existed between team psychological safety and performance outputs from concept screening. Specifically, we hypothesized that as team psychological safety decreased, the incidence of ownership bias would increase. This is based on using ownership bias as a proxy to measure the lack of sense of the importance of collaboration, where team members select their own ideas without considering others' ideas [66]. This is particularly critical for subsequent design outputs, as selection processes can impact outputs such as the final design [67]. Furthermore, we hypothesized that as perceptions of psychological safety decreased at the individual level, incidence of ownership bias would increase [58].

Similar to RQ1, prior to the analysis, the validity of team aggregations of psychological safety at Time Point 3 was verified through interrater agreement calculations (r_{wg} = 0.87, ICC(1) = 0.129, ICC(2)=0.354 [73]. In addition, statistical assumptions were checked. Specifically, requirements for homoscedasticity were met, as assessed by visual inspection of a plot of standardized residuals versus standardized predicted values. Furthermore, normality was confirmed by visually inspecting the histograms and Q-Q plots.

Once assumptions were verified, six linear regression analyses were conducted at the team level as well as an investigation of individual perceptions of psychological safety for all six cases using a multilevel analysis [77]. Four of the six cases are described here, where the remaining two analyses were variations of percentage of team members' ideas selected, similar to that of the idea goodness cutoffs used in percentage of own ideas selected. It is important to state that teams where individuals did not evaluate their own ideas were removed from analyses for selecting their own ideas, leaving 65 teams to be analyzed. In the case where not all team members evaluated all others' ideas, those teams were removed for analyses focused on individuals selecting others' ideas.

The first linear regression used the independent variable of psychological safety during Time Point 3, concept screening, and the dependent variable percentage of own ideas selected. The results failed to show a statistically significant relationship between psychological safety and percentage of own ideas selected, $F(1, 63) = 0.813$, $p = 0.371$. To see if this ownership bias was contingent on the quality of the ideas, a second linear regression analysis used the dependent variable was percentage own ideas with goodness score below 0.5. However, the results failed to reveal a statistically significant correlation, $F(1, 63) = 0.982$, $p = .325$. Finally, a third linear regression analysis was conducted with percentage own ideas with goodness score above 0.5. However, the results again revealed no statistically significant relationship, $F(1, 63) = 0.032$, $p = 0.858$. Furthermore, none of the results revealed any statistical significance for ideas being selected by other team members.

These results refute our hypothesis in the sense that ownership bias is not associated with lower team psychological safety nor perceptions of psychological safety due to the lack of statistical significance. Furthermore, the halo effect [68] is not even present, where team members tend to select others' ideas over their own. These results convey that while psychological safety shared a positive relationship with team perceptions of idea goodness in RQ1, RQ2's findings suggest that idea quality perceptions for selecting others' ideas are unrelated to psychological safety.

2.6 Discussion

The main goal of this study was to explore the role of psychological safety on engineering team productivity in the conceptual phases of the design process. The main findings of this study were as follows:

- Psychological safety was significantly negatively correlated with the number of ideas (fluency) produced by a team.

- Psychological safety was significantly positively related to team idea goodness.
- Ownership bias failed to share a relationship with both the team level and individual perceptions of psychological safety.

This result indicates that while psychological safety may not increase team productivity in terms of the number of ideas produced, it may impact team effectiveness in coming up with viable candidate ideas to move forward in the design process. The finding that psychological safety was significantly and negatively related to the total number of ideas generated (fluency) by the team alludes to literature that emphasizes the dark side of psychological safety in terms of social loafing [75] and unethical behaviors [76]. Furthermore, while prior research indicates that members who generate ideas in a team tend to offer more ideas than individuals working independently [54], this was not the case in our study. Although feeling interpersonally safe to generate novel ideas may overcome the evaluation apprehension or fear of being judged and looking unintelligent [6, 12, 34], other factors may bear more weight in this process, such as other barriers to brainstorming, such as production blocking and social loafing [52, 55]. This can be seen where production blocking allows only one person to speak at a time [52], and individuals do not hold themselves accountable as a result of social loafing [55], which may be explained by the minimum idea fluency from one of the individuals decreasing as psychological safety increases. However, the ideas generated during the concept generation stage tended to be of high subjective quality based on the idea goodness ratings [68]. Because idea goodness can be facilitated by feelings of trust within the team, this may have influenced psychological safety in a positive manner [65], and thus idea goodness increased.

In contrast to *concept generation*, psychological safety influenced the *concept screening* stage in a positive manner at the level of idea goodness. When team members feel that it is safe to take risks, they may be more likely to accept others for being different, value each other's skills, and offer honest, negative feedback about the quality of the generated ideas without team members feeling as if they have been rejected or their efforts undermined. When team members feel that it is safe to take risks, they may be more likely to accept others for being different, value each other's skills, and offer honest, negative feedback about the quality of the generated ideas without team members feeling as if they have been rejected or their efforts undermined [6]. When ideas can be critically vetted without threatening the egos of teammates [11], better solutions result from the perspective of idea goodness [68], as demonstrated in these study results. In the creative process of engineering design [41], *concept screening* is where the benefits of psychological safety are salient. This is also apparent from the perspective of ownership bias, where critical signs of bias would've been apparent in the dependent variable of average percentage of own ideas with low goodness selected [68, 70]. However, there was no statistically significant correlation, exhibiting that ownership bias and psychological safety were not strongly related.

One conclusion of our results is that psychological safety exerts differential effects on creative processes. For example, psychological safety was found to be significantly and negatively associated with idea fluency during *concept generation*, whereas idea goodness was positively related during *concept screening*. However, psychological safety was found to not be impactful for the percentage of own ideas selected nor team members' ideas selected during the examination of ownership bias during *concept screening*, meaning that increases in psychological safety does not impact the percentage of ideas that the individual chooses of their own or the percentage that the team chooses of others' ideas.

2.7 Conclusions and Future Work

While this study presents some interesting results to further broaden our view of how psychological safety plays a role in engineering design student project trajectories, such results do not come without limitations. First, many factors can influence the number of ideas an individual proposes during concept generation; these might include their amount of tacit knowledge about the design problem or a tendency to shyness, among others. Specifically, both design task [47] and prior background knowledge [48] can impact design outputs, potentially impacting how many ideas an individual feels that they can generate (idea fluency), or how well they understand the task to feel safe to agree with others' ideas (idea goodness). In addition, according to previous work related to creativity [25], other individual qualities can influence or inhibit their creativity. Because individual characteristics may influence idea fluency during *concept generation*, it may be difficult to determine the impact of psychological safety on concept generation, thus limiting our results. Specifically, some students may produce ideas at a slower rate than other students, where the limited time to produce ideas may have placed unintended bounds on teams' idea fluency. Furthermore, the lack of team interaction at such an early stage in the design process may contribute to the outcome of a weak correlation, as psychological safety requires a significant amount of interaction and takes time to manifest [7].

Furthermore, the combination of idea goodness and team psychological safety does not tell the full story behind interactions between specific individuals during *concept screening*, as psychological safety is a team construct [6]. For example, if one member does not get along with one other individual and purposely does not consider their ideas, this would unfairly decrease the idea goodness of that individual's ideas, despite this team having relatively high psychological safety. However, this can be analyzed through an ownership bias lens, where an idea generated by the original idea generator is selected, despite having a lower idea goodness based on the ratings of others in the same team [70]. That being said, the idea goodness ratings in this study were simplified in comparison to an earlier study [70], which may be why very good ideas were not rated as highly, and very poor ideas were not rated as negatively. Because these analyses rely on definitions from Toh et al. [68] to separate the "poor" ideas from "good" ideas while using a "majority rules" method, binning the results in such a way removes some of the details of the degree of goodness. Furthermore, as psychological safety is a team construct and is aggregated to the team level [6], the ownership bias calculations were aggregated to the team level as well. This makes it difficult to detect whether ownership bias is occurring in just one or two individuals or the team as a whole. In addition, results that show that any incidences of ownership bias could be due to some other factors beyond psychological safety, such as gender [68], which were not explored in this study.

In addition to limitations presented in *concept screening* analyses, full interpretation of the idea goodness scores is limited until more qualitative data is gathered from team members' reasonings for how they decide to select others' ideas. While higher psychological safety can increase a team's likelihood for risk-taking, it is also known to impact an individual's ability to speak up in a group when they believe there is an issue [6]. Therefore, rating ideas poorly could be a way of "speaking up." The willingness to speak up is critical, as the success of a final design is largely dependent on the concept generation and concept selection stages of a project [10]. In other words, if poor ideas are not detected and removed in the early stages of a design, the end result could be catastrophic. On the other hand, the inability to manage cognitive gaps may prevent team members from considering others' ideas, preventing the team from exploring the solution space [27, 28]. While results favor the risk-taking aspect, further analysis is needed to ensure this. Importantly, the ratings from this study do not take the originality of ideas into account, which can further confound results. Furthermore, while idea goodness through non-expert ratings has been validated in other studies [68, 70], we understand that individual perceptions of an idea's quality can be subjective. To take a more objective approach, quasi-expert ratings of ideas from incremental to radical can be used in conjunction with KAI [42, 43] and team psychological safety to explain how individuals' feelings about their team and their inherent traits can impact design outputs.

In addition to specific limitations in *concept generation* and *concept screening*, the causal direction of psychological safety should be discussed as well. Because the psychological safety survey is taken at the end of class right after the activity, we assume that the psychological safety scores would not have been impacted much, if at all, throughout the duration of each activity. This is based on the notion that psychological safety takes time to manifest [7], therefore not much of a change is expected before and after each activity at one of the time points. Furthermore, the building and waning of psychological safety could take place outside of the classroom due to other forms of communication outside of class time when working on assignments and/or studying together [71], making the activity itself less likely to cause the team psychological safety to change. As this study is one of the first to examine psychological safety through multiple time points, and while we do not know the causal direction, it is beneficial to understand how psychological safety impacts team engineering design outputs. This can be critical for establishing future intervention methods aimed to improve psychological safety, as understanding whether or not whether there is any relationship between psychological safety and design outputs substantiates the potential benefit of focusing on increasing psychological safety to improve team performance. While recent work has focused on these initiatives through role-based interventions [21], more work is needed to understand how such interventions can feed into engineering design team performance.

Along with the lack of causal direction of the activities, it is also important to discuss potential confounding effects of how KAI may impact concept generation and concept screening outputs. While these outputs may have an impact, our preliminary analyses have shown that KAI shows no statistical significance at all time points, leading us to believe that KAI is not impactful on productivity outputs. Therefore, investigation of the potential impact of cognitive style (via KAI) on psychological safety would be more suitable for rating ideas from incremental to radical [42, 43].

Although the current study sheds some light on how psychological safety impacts the activities of students during *concept generation* and *concept screening*, further investigation must be done to determine what types of verbal interactions impact the building or waning of psychological safety in engineering design teams along the way. Based on reviewing the team psychological safety scores at each time point, no particular trend could be depicted as most teams' scores fluctuated throughout the trajectory of the design project, suggesting that some underlying factors could point to drops in psychological safety at various time points for teams. Similar to the trends exhibited in Miller et al. [9] which specifically looked at the evolution of psychological safety over the time steps, some teams started out with a high team psychological safety score and increased throughout the course of the project as the team members grew closer with each other, whereas some teams experienced a dip in team psychological safety at Time Point 2 (concept generation), Time Point 3 (concept screening), or Time Point 5 (final deliverables deadline). In general, psychological safety scores tended to be on the high end (close to 7), and while the cause for this sample remains unclear, work outside of engineering education showed that external factors, such as inherent cultural and learning behaviors [8], can contribute to either high or low trends in psychological safety for specific groups.

Furthermore, although design outputs during concept generation and concept screening have been gathered, outputs of the end product at Time Point 5 can be examined in a future study to develop an expanded view of how team psychological safety impacts the final product from each team.

In addition to teams' psychological safety at individual points, a positive skew in psychological safety appeared for most teams, and team-level aggregate scores may have obscured individual members who reported low psychological safety, which is a point team scholars have highlighted [78]. Although individual perceptions of psychological safety were statistically insignificant in most incidences of analyzing engineering design outputs, further analysis is needed to uncover why some members had lower perceptions of psychological safety compared to others. These points suggest that a qualitative analysis of audio recordings [35] during these time points is important in determining how the interactions impact students' abilities to perform optimally relative to their abilities during *concept generation* and *concept screening*. Finally, these results focused on a student group of designers, which may produce different design outputs from industry professionals. Therefore, the generalizability of these results is limited to design groups in education.

2.8 References

[1] Williamson, J. M., Lounsbury, J. W., and Han, L. D., 2013, "Key personality traits of engineers for innovation and technology development," Journal of Engineering and Technology Management, 30(2), pp. 157-168.
[2] Cohen, S. G., and Bailey, D. E., 1997, "What makes teams work: Group effectiveness research from the shop floor to the executive suite," Journal of management, 23(3), pp. 239-290.
[3] Mathieu, J., Maynard, M. T., Rapp, T., and Gilson, L., 2008, "Team effectiveness 1997-2007: A review of recent advancements and a glimpse into the future," Journal of management, 34(3), pp. 410-476.
[4] Rozovsky, J., 2015, "The five keys to a successful Google team," Retrieved from https://rework.withgoogle.com.
[5] Duhigg, C., 2016, "What Google learned from its quest to build the perfect team," The New York Times Magazine.

[6] Edmondson, A., 1999, "Psychological safety and learning behavior in work teams," Administrative science quarterly, 44(2), pp. 350-383.
[7] Edmondson, A. C., and Lei, Z., 2014, "Psychological Safety: The History, Renaissance, and Future of an Interpersonal Construct," Annual Review of Organizational Psychology and Organizational Behavior, 1(1), pp. 23-43.
[8] Frazier, M. L., Fainshmidt, S., Klinger, R. L., Pezeshkan, A., and Vracheva, V., 2017, "Psychological Safety: A Meta-Analytic Review and Extension," Personnel Psychology, 70(1), pp. 113-165.
[9] Miller, S., Marhefka, J., Heininger, K., Jablokow, K., Mohammed, S., and Ritter, S., "The Trajectory of Psychological Safety in Engineering Teams: A Longitudinal Exploration in Engineering Design Education," Proc. ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[10] Dylla, N., 1991, "Thinking methods and procedures in mechanical design," PhD, Technical University of Munich, Munich, Germany.
[11] Edmondson, A. C., 2003, "Speaking Up in the Operating Room: How Team Leaders Promote Learning in Interdisciplinary Action Teams," Journal of Management Studies, 40(6), pp. 1419-1452.
[12] Burningham, C., and West, M. A., 1995, "Individual, Climate, and Group Interaction Processes as Predictors of Work Team Innovation," Small Group Research, 26(1), pp. 106-117.
[13] McGourty, J., Shuman, L., Besterfield-Sacre, M., Atman, C., Miller, R., Olds, B., Rogers, G., and Wolfe, H., 2002, "Preparing for ABET EC 2000: Research-based assessment methods and processes," International Journal of Engineering Education, 18(2), pp. 157-167.
[14] Loughry, M. L., Ohland, M. W., and DeWayne Moore, D., 2007, "Development of a Theory-Based Assessment of Team Member Effectiveness," Educational and Psychological Measurement, 67(3), pp. 505-524.
[15] Chhabria, K., Black, E., Giordano, C., and Blue, A., 2019, "Measuring health professions students' teamwork behavior using peer assessment: Validation of an online tool," Journal of Interprofessional Education & Practice, 16.
[16] Hastings, E. M., Jahanbakhsh, F., Karahalios, K., Marinov, D., and Bailey, B. P., 2018, "Structure or Nurture? The Effects of Team-Building Activities and Team Composition on Team Outcomes," Proceedings of the ACM on Human-Computer Interaction, 2(CSCW), pp. 1-21.
[17] Beigpourian, B., 2019, "Using CATME to document and improve the effectiveness of teamwork in capstone courses," Proc. 2019 ASEE Annual Conference and Exposition.
[18] Beigpourian, B., Luchini, F., Ohland, M., and Ferguson, D., "Psychological Safety as an Effective Measurement in Engineering Classrooms," Proc. 2019 ASEE Annual Conference and Exposition.
[19] McNeil, J., Corley, W. B., and Hieb, J. L., "Investigating psychological safety in a flipped engineering course," Proc. 2017 IEEE Frontiers in Education Conference (FIE), IEEE, pp. 1-4.

[20] Beckman, S. L., and Barry, M., 2007, "Innovation as a learning process: Embedding design thinking," California management review, 50(1), pp. 25-56.
[21] Drum, A., Cole, C., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., "Let's Role Play! The Impact of Video Frequency and Role Play on the Utility of a Psychological Safety Team Intervention," Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[22] Dym, C. L., and Little, P., 2014, Engineering design: A project-based introduction, John Wiley and sons.
[23] Plan, E. T., and Khandani, S., 2005, "Engineering design process."
[24] Pugh, S., 1991, Total Design: Integrated Methods for Successful Product Engineering, Addison-Wesley.
[25] Amabile, T. M., 1988, "A model of creativity and innovation in organizations," Research in organizational behavior, 10(1), pp. 123-167.
[26] Cooper, R. G., and De Brentani, U., 1984, "Criteria for screening new industrial products," Industrial Marketing Management, 13(3), pp. 149-156.
[27] Kirton, M., 1976, "Adaptors and innovators: A description and measure," Journal of Applied Psychology, 61(5), pp. 622-629.
[28] Kirton, M. J., 2011, Adaption-Innovation in the Context of Diversity and Change, Routledge, London, UK.
[29] Jablokow, K. W., and Booth, D. E., 2006, "The impact and management of cognitive gap in high performance product development organizations," Journal of Engineering and Technology Management, 23(4), pp. 313-336.
[30] Jonassen, D. H., and Kim, B., 2010, "Arguing to learn and learning to argue: Design justifications and guidelines," Educational Technology Research and Development, 58(4), pp. 439-457.
[31] Jonassen, D. H., and Cho, Y. H., 2011, "Fostering Argumentation While Solving Engineering Ethics Problems," Journal of Engineering Education, 100(4), pp. 680-702.
[32] Edmondson, A. C., 2002, "The Local and Variegated Nature of Learning in Organizations: A Group-Level Perspective," Organization Science, 13(2), pp. 128-146.
[33] Edmondson, A. C., Bohmer, R. M., and Pisano, G. P., 2001, "Disrupted Routines: Team Learning and New Technology Implementation in Hospitals," Administrative Science Quarterly, 46(4), pp. 685-716.
[34] Edmondson, A. C., 2002, Managing the risk of learning: Psychological safety in work teams, Cambridge, MA: Division of Research, Harvard Business School.
[35] Neal, J. W., Neal, Z. P., VanDyke, E., and Kornbluh, M., 2015, "Expediting the Analysis of Qualitative Data in Evaluation:A Procedure for the Rapid Identification of Themes From Audio Recordings (RITA)," American Journal of Evaluation, 36(1), pp. 118-132.
[36] Kark, R., and Carmeli, A., 2009, "Alive and creating: the mediating role of vitality and aliveness in the relationship between psychological safety and creative work involvement," Journal of Organizational Behavior, 30(6), pp. 785-804.
[37] Amabile, T. M., 1982, "Social psychology of creativity: A consensual assessment technique," Journal of Personality and Social Psychology, 43(5), pp. 997-1013.

[38] Toh, C. A., and Miller, S. R., 2016, "Choosing creativity: the role of individual risk and ambiguity aversion on creative concept selection in engineering design," Research in Engineering Design, 27(3), pp. 195-219.
[39] Toh, C. A., and Miller, S. R., 2016, "Creativity in design teams: the influence of personality traits and risk attitudes on creative concept selection," Research in Engineering Design, 27(1), pp. 73-89.
[40] Heininger, K., Chen, H.-E., Jablokow, K., and Miller, S. R., "How Engineering Design Students' Creative Preferences and Cognitive Styles Impact Their Concept Generation and Screening," Proc. ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[41] Christiaans, H., 2002, "Creativity as a Design Criterion," Creativity Research Journal, 14(1), pp. 41-54.
[42] Silk, E. M., Daly, S. R., Jablokow, K. W., and McKilligan, S., 2019, "Incremental to radical ideas: paradigm-relatedness metrics for investigating ideation creativity and diversity," International Journal of Design Creativity and Innovation, 7(1-2), pp. 30-49.
[43] Silk, E. M., Daly, S. R., Jablokow, K. W., Yilmaz, S., Rechkemmer, A., and Wenger, J. M., "Using paradigm-relatedness to measure design ideation shifts," Proc. American Society for Engineering Education (ASEE) Annual Conference.
[44] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2021, "The Crowd Predicts a Paradigm Shift: Exploring the Relationship Between Cognitive Style and the Paradigm-Relatedness of Design Solutions," Proc. ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[45] Kessel, M., Kratzer, J., and Schultz, C., 2012, "Psychological Safety, Knowledge Sharing, and Creative Performance in Healthcare Teams," Creativity and Innovation Management, 21(2), pp. 147-157.
[46] Choo, A. S., Linderman, K., and Schroeder, R. G., 2007, "Social and Method Effects on Learning Behaviors and Knowledge Creation in Six Sigma Projects," Manag. Sci., 53(3), pp. 437-450.
[47] Tekmen-Araci, Y., and Mann, L., 2019, "Instructor approaches to creativity in engineering design education," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233(2), pp. 395-402.
[48] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2007, "Relative accessibility of domain knowledge and creativity: The effects of knowledge activation on the quantity and originality of generated ideas," Journal of Experimental Social Psychology, 43(6), pp. 933-946.
[49] Paulus, P., 2000, "Groups, teams, and creativity: The creative potential of idea-generating groups," Applied Psychology, 49(2), pp. 237-262.
[50] Massetti, B., 1996, "An Empirical Examination of the Value of Creativity Support Systems on Idea Generation," MIS Quarterly, 20(1), pp. 83-97.
[51] Baer, M., and Frese, M., 2003, "Innovation is not enough: climates for initiative and psychological safety, process innovations, and firm performance," Journal of Organizational Behavior, 24(1), pp. 45-68.

[52] Furnham, A., 2000, "The Brainstorming Myth," Business Strategy Review, 11(4), pp. 21-28.
[53] Putman, V. L., and Paulus, P., 2009, "Brainstorming, Brainstorming Rules and Decision Making," The Journal of Creative Behavior, 43(1), pp. 29-40.
[54] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2006, "Productivity is not enough: A comparison of interactive and nominal brainstorming groups on idea generation and selection," Journal of Experimental Social Psychology, 42(2), pp. 244-251.
[55] Karau, S. J., and Williams, K. D., 1993, "Social loafing: A meta-analytic review and theoretical integration," Journal of Personality and Social Psychology, 65(4), pp. 681-706.
[56] Osburn, H. K., and Mumford, M. D., 2006, "Creativity and Planning: Training Interventions to Develop Creative Problem-Solving Skills," Creativity Research Journal, 18(2), pp. 173-190.
[57] Daly, S. R., Mosyjowski, E. A., and Seifert, C. M., 2014, "Teaching Creativity in Engineering Courses," Journal of Engineering Education, 103(3), pp. 417-449.
[58] Paulus, P. B., and Brown, V. R., 2007, "Toward More Creative and Innovative Group Idea Generation: A Cognitive-Social-Motivational Perspective of Brainstorming," Social and Personality Psychology Compass, 1(1), pp. 248-265.
[59] Reiter-Palmon, R., and Arreola, N. J., 2015, "Does Generating Multiple Ideas Lead to Increased Creativity? A Comparison of Generating One Idea vs. Many," Creativity Research Journal, 27(4), pp. 369-374.
[60] Mirabito, Y., and Goucher-Lambert, K., "The Role of Idea Fluency and Timing on Highly Innovative Design Concepts," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering ConferenceV008T08A035.
[61] Walumbwa, F. O., and Schaubroeck, J., 2009, "Leader personality traits and employee voice behavior: Mediating roles of ethical leadership and work group psychological safety," Journal of Applied Psychology, 94(5), pp. 1275-1286.
[62] Onarheim, B., and Christensen, B. T., 2012, "Distributed idea screening in stage–gate development processes," Journal of Engineering Design, 23(9), pp. 660-673.
[63] Beggan, J. K., 1992, "On the social nature of nonsocial perception: The mere ownership effect," Journal of Personality and Social Psychology, 62(2), pp. 229-237.
[64] Conchie, S. M., Donald, I. J., and Taylor, P. J., 2006, "Trust: Missing Piece(s) in the Safety Puzzle," Risk Analysis, 26(5), pp. 1097-1104.
[65] Edmondson, A. C., Kramer, R. M., and Cook, K. S., 2004, "Psychological safety, trust, and learning in organizations: A group-level lens," Trust and distrust in organizations: Dilemmas and approaches, 12, pp. 239-272.
[66] Nikander, J. B., Liikkanen, L. A., and Laakso, M., 2014, "The preference effect in design concept evaluation," Design Studies, 35(5), pp. 473-499.
[67] Cooper, R. G., Edgett, S. J., and Kleinschmidt, E. J., 2002, "Optimizing the Stage-Gate Process: What Best-Practice Companies Do—I," Research-Technology Management, 45(5), pp. 21-27.
[68] Toh, C. A., Strohmetz, A. A., and Miller, S. R., 2016, "The Effects of Gender and Idea Goodness on Ownership Bias in Engineering Design Education," Journal of Mechanical Design, 138(10), p. 101105.

[69] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003, "Metrics for measuring ideation effectiveness," Design Studies, 24(2), pp. 111-134.
[70] Zheng, X., and Miller, S. R., 2019, "Is Ownership Bias Bad? The Influence of Idea Goodness and Creativity on Design Professionals Concept Selection Practices," Journal of Mechanical Design, 141(2), p. 021106.
[71] Vaughan, N., Nickle, T., Silovs, J., and Zimmer, J., 2011, "Moving To Their Own Beat: Exploring How Students Use Web 2.0 Technologies To Support Group Work Outside Of Class Time," Journal of Interactive Online Learning, 10(3).
[72] Fisher, R. A., 1925, "Theory of Statistical Estimation," Mathematical Proceedings of the Cambridge Philosophical Society, 22(5), pp. 700-725.
[73] LeBreton, J. M., and Senter, J. L., 2008, "Answers to 20 Questions About Interrater Reliability and Interrater Agreement," Organizational Research Methods, 11(4), pp. 815-852.
[74] Cohen, J., 1988, Statistical power analysis for the behavioral sciences, L. Erlbaum Associates, Hillsdale, N.J.
[75] Deng, H., Leung, K., Lam, C. K., and Huang, X., 2019, "Slacking Off in Comfort: A Dual-Pathway Model for Psychological Safety Climate," Journal of Management, 45(3), pp. 1114-1144.
[76] Pearsall, M. J., and Ellis, A. P. J., 2011, "Thick as thieves: The effects of ethical orientation and psychological safety on unethical team behavior," Journal of Applied Psychology, 96(2), pp. 401-411.
[77] Kozlowski, S. W. J., Chao, G. T., Grand, J. A., Braun, M. T., and Kuljanin, G., 2013, "Advancing Multilevel Research Design:Capturing the Dynamics of Emergence," Organizational Research Methods, 16(4), pp. 581-615.
[78] Mathieu, J. E., Gallagher, P. T., Domingo, M. A., and Klock, E. A., 2019, "Embracing Complexity: Reviewing the Past Decade of Team Effectiveness Research," Annual Review of Organizational Psychology and Organizational Behavior, 6(1), pp. 17-46.

CHAPTER 3

AN EXPLORATION OF THE RELATIONSHIP BETWEEN COGNITIVE STYLE, PSYCHOLOGICAL SAFETY, AND THE PARADIGM-RELATEDNESS OF DESIGN SOLUTIONS IN ENGINEERING DESIGN TEAMS IN EDUCATION

This paper is based on a conference paper previously published in the International Design Engineering Technical Conference and Computers and Information in Engineering Conference [1]. The extension of this paper will be submitted for publication in the Journal of Mechanical Design in July 2022. This work is multiple-authored by Courtney Cole, Jacqueline Marhefka, Dr. Kathryn Jablokow, Dr. Susan Simkins, Dr. Sarah Ritter, and Dr. Scarlett Miller. Courtney Cole is the lead author on the paper, and Dr. Scarlett Miller and Dr. Kathryn Jablokow helped advise the work.

3.1 Abstract

Nearly 60 years ago, Thomas Kuhn revolutionized how we think of scientific discovery and innovation when he identified that scientific change can occur in incremental developments that improve upon existing solutions, or it can occur as drastic change in the form of a paradigm shift. In engineering design, both types of scientific change are critical when exploring the solution space. However, most methods of examining design outputs look at whether an idea is creative or not and not the type of creativity that is deployed. Without knowing how to identify who will generate ideas that fit a certain paradigm, we do not know how to build teams that can develop ideas that better explore the solution space. This study provides the first attempt at answering this question through an empirical study with 64 engineering design student teams over the course of a 4- and 8-week design project. Specifically, we sought to identify the role of cognitive style using KAI score, derived from Kirton's Adaption-Innovation (A-I) theory, on the paradigm-relatedness of ideas generated by individuals and teams. Results showed that design task significantly impacted the paradigm-relatedness categorization of individual ideas from concept generation, and the availability of ideas from this stage impacted the paradigm-relatedness of team-selected concepts. Additionally, KAI diversity was positively related to a greater likelihood of teams' functional prototypes being categorized as paradigm-challenging or paradigm-breaking. Results support the use of paradigm-relatedness as an idea rating metric.

3.2 Introduction

Thomas Kuhn revolutionized the way that we think about scientific discovery and innovation nearly 60 years ago in his landmark book, *The Structure of Scientific Revolutions* [2]. It was there that Kuhn defined two different types of scientific change: incremental developments or "normal science" and scientific revolutions that involve the ever-evasive "paradigm shift" [2], *"an important change that happens when the usual way of thinking about something is replaced by a new or different way"*[3]. In other words, incremental developments often lead to refined versions of existing solutions that excel by performing better in their primary or a related context [4], while paradigm shifting ideas lead to radical changes that allow us to approach a problem from unexpected angles or to connect concepts that at first seem unrelated [4]. In recent times, Kuhn's work has been commended for suggesting that these two creative problem-solving perspectives do not just coexist, but are interrelated and should be considered in combination [5]. In a design context, Kuhn's work is particularly influential when design problems are wicked problems [6], or problems that are societal and less structured, and the information needed to understand the problem depends on generating a vast array of ideas [7]. While we recognize the importance of both incremental and radical ideas, we focus on Kuhn's emphasis on radical, or "paradigm shifting" [2] ideas.

Through the concept of paradigms, Kuhn encouraged a paradigm shift of his own by pushing the scientific community to tackle problems of various kinds in ways beyond typical methods [8]. In Kuhn's book, he stated, "Under *normal conditions* the research scientist is not an *innovator* but a solver of puzzles, and the puzzles upon which he concentrates are just those which he believes can be both stated and solved within the existing scientific tradition," [2] (p. 170). When faced with a challenge outside of such *normal conditions*, Kuhn postulated that there may be some underlying attributes or experiences of people who are more likely to develop these radical ideas, foreshadowing (while not explicitly proposing) the concept of an individual's *cognitive style*. Specifically, he suggested that people who come up with paradigm shifting ideas are typically young or very new to the field whose paradigm they change – or people who are not committed by prior practice to the traditional rules of "normal science," [2].

If we know paradigm shifts are vital to technical discoveries, then a key question is: are there characteristics of individuals (or teams) that can predict paradigm-shifting ideas? One trait that may impact a designer's tendency to develop paradigm-shifting ideas is their cognitive style. Roughly a decade after Kuhn's book was published, Kirton's Adaption-Innovation (A-I) theory was validated, pointing to *cognitive style* as a factor that can influence the types of ideas and solutions a person generates through that individual's innate cognitive preference for structure [9]. Here, "A-I theory" refers to the theory itself and not the metric that is derived from it. Using A-I theory, an individual's cognitive style falls somewhere within the range of highly adaptive (i.e., strongest preference for structure) to highly innovative (i.e., weakest preference for structure) [10]. In practice, more innovative individuals are less structured thinkers who tend to approach tasks from unsuspected angles, challenge problem constraints, and are more disruptive risk-takers [10, 11]. In contrast, more adaptive individuals are more structured thinkers who refine current systems, focus on precision, reliability, and efficiency, and engage in prudent risk-taking [10, 11]. A-I theory is based on the assumption that all individuals, of all cognitive styles, are creative [10], which dovetails nicely with Kuhn's supposition that both normal science and paradigm shifts are necessary for science to progress [1].

To support its practical use in context, the Kirton Adaption-Innovation Inventory (KAI), which was derived from A-I theory [9], has been validated for the general population and for other sub-groups, including engineers [9, 10, 12]. Specifically, KAI has been used in engineering design research [13-15], where cognitive style was shown to significantly predict "creative idea generation" using the Consensual Assessment Technique (CAT) [15]. Furthermore, this study found there to be lack of significant relationship with the screening of creative ideas [15]. However, the CAT dismisses some ideas as "not creative," limiting a full interpretation of the data through the A-I theory lens. While relatively new, *paradigm-relatedness* as a rating technique overcomes this limitation by mirroring A-I theory and supporting a more diverse definition of creativity [16, 17].

Researchers first defined *paradigm-relatedness* as a measure of an idea's creative style, "independent of and orthogonal to the creativity level" [18] (p. 89). The concept was taken further by defining categories of *paradigm-relatedness* based on the elements, relationships, and focus of a design concept [19]. Although it can be more difficult to achieve high interrater-reliability when breaking up paradigm-relatedness into components such as *elements*, *relationships*, *constraints*, and *focus* [17], a *category-based* (which involves separating ideas into one of a few broad categories) metric approach is still recommended for assessing large sets of ideas, because it is faster to apply and more reliable [17].

In addition to exploring cognitive style and paradigm-relatedness at the individual level, it is also important to analyze the impact at the team level as well. This is important because the path to creative results is less clear at the team level, and there is much debate over *how* to promote team creativity [20, 21] due to the complex dynamics of teams [22]. Specifically, when team members' cognitive styles are diverse, cognitive gaps are created. A team can leverage this style diversity by approaching problems using different perspectives, or they can succumb to conflicts that disrupt the team's efforts [10]. Cognitive gaps can be measured in different ways, including the standard deviation of a team's KAI score distribution [13] (referred to as *cognitive diversity* [23]). Cognitive style can also be measured at the team level through average measures (e.g., a team's average KAI score). Team research shows that computing the average of team members' scores (referred to as *cognitive elevation* [23]) can be viewed as a collective value that represents the team as a whole [24, 25], as additive aggregation models assume that all team members' scores should be equally represented (e.g., [26]). However, because mean values on diversity measures can be confounded with within-group standard deviations [27], controlling for mean can help depict a clearer view of cognitive diversity's impacts on design outputs. Despite prior team research using KAI and the assessment of design solutions, the impact of cognitive style on the paradigm-relatedness of design outcomes remains unclear and largely uninvestigated. Understanding this impact is important, because the diversity of strategy and approach in generating both incremental and radical ideas within a team can help teams explore a wider solution space, and thus increase the potential for a successful design [28].

To take advantage of the benefits of conflict due to cognitive gap, psychological safety, or the belief that individuals in a team can speak up and take risks without criticism [29], could serve as a factor that influences how teams resolve or ignore conflict, impacting how team members interact when issues arise [29, 30]. Some studies have even pointed to a connection between trust (which mediates psychological safety [31]) and the sharing of creative ideas [32, 33]. Thus, the inclusion of psychological safety in predicting creative outputs shows potential as a critical component of understanding how teams generate and select design outputs.

In consideration of the prior work on factors that may impact the type of design outputs, the objective of this paper was to explore the relationship between cognitive style, psychological safety, and the paradigm-relatedness of design outputs during the *concept generation*, *concept selection*, and *prototyping* stages of the design process. Specifically, we sought to understand this impact at both the individual and team level. The results of this study provide empirical evidence of design task, the availability of generated concepts, and cognitive style diversity on the paradigm-relatedness of design outputs at various stages. These results can be used to identify directions for future work in exploring interventions that promote certain types of design outputs.

3.3 Related Work

The engineering design process can be simplified into three phases consisting of generation, evaluation (e.g., concept screening), and communication [34]. During concept generation, team members are encouraged to produce creative ideas, or ideas that are both novel and useful [35]. This stage is critical to overall performance, as the availability of creative ideas is a precursor to evaluation and part of the formula for pushing innovation [36]. Concept generation practices tend to be dependent on individuals' background knowledge of the problem [37], which is why engineering design students are given time to become familiar with their design prompt. On the other hand, concept screening practices rely on rating ideas as consider/do not consider to economize time via eliminating potentially unsuccessful ideas [38]. From there, concepts are selected using more involved decision-making tactics [39] and prototyping practices rely on designers conveying their design [40]. Prototyping shares some similarities with concept screening as well, where prior research shows that engineering design students tend to perceive more unique ideas as riskier if the fidelity is lower [41]. Interestingly, prior work showed that while design task can impact creative outputs across these stages, creative concepts chosen from the generation stage do not retain their level of creativity and novelty as they reach the final conceptual design stage [42], which coincides with emphasis on technical feasibility in engineering design team discussions during the selection process [43]. Despite knowing such information about creative idea generation, selection, and prototyping on the surface, the cognitive mechanisms behind the paradigm-relatedness of individuals' design solutions have seen limited exploration [18, 19], particularly in engineering design. Furthermore, how psychological safety impacts such outputs at the team level remains unclear as well, supporting the need for further investigation that builds on prior work [44].

3.3.1 Potential Impact of Cognitive Style and Psychological Safety on Creative Design Outputs

Throughout the engineering design process, team design outputs such as the perceived quality and quantity of ideas may be subject to varying levels of psychological safety [44]. However, other factors that commence at the individual level are important to consider as well. Specifically, to predict the style of outputs with more precision, individuals' cognitive problem-solving processes are important to consider when team members collaborate. Interestingly, research on this topic started to grow nearly 50 years ago when Kirton's Adaption-Innovation (A-I) theory was validated, pointing to cognitive style as a factor that can influence the types of ideas and solutions a person generates through that individual's innate cognitive preference for structure [9]. Cognitive style from the perspective of categorizing individuals as somewhere from adaptive to innovative provides a way to understand how team members of varying characteristics may interact. Since its inception, the influence of Kirton's Adaption-Innovation (A-I) theory grew from a 32-item inventory (i.e., KAI) that could characterize an individual's preferences for problem solving [9]. Kirton's A-I theory and the KAI inventory are both built on the key assumption that there are people who prefer "to do things better" (Adaption) and those who prefer "to do things differently" (Innovation), and are both creative (p. 622) [9]. Varying amounts of adaption and innovation can be beneficial, depending on the problem-solving scenario. In this context, Adaption and Innovation exist on opposite sides of continuous spectrum of cognitive style, which is defined as the stable, characteristic cognitive preference that describes how people seek or respond to change [45]. Cognitive style differs from cognitive level, which defines an individual's capacity for engaging in problem-solving and creative behavior [10]. When generating solutions to problems, it is noted that innovators tend to filter their ideas less, stretch the problem space boundaries, and rely less on group cohesion. Conversely, adaptors tend to screen their ideas more carefully, explore thoroughly inside the problem space boundaries, and promote group cohesion [14].

In contrast with what we know about cognitive style and the generation of ideas, the relationship between selection processes and cognitive style has not seen as much attention. While prior work has covered how selection methods can influence the idea sets that survive across the design stages that end with the final concept [39], and that individual traits such as risk aversion can impact what concepts an individual may select [46], work on how cognitive style plays a role in selection processes remains unclear. Although prior work shows promise for using cognitive style as a means to predict the types of ideas individuals may screen [15], this study is one of the first to examine the relationship between cognitive style and the paradigm-relatedness of concepts that teams select for prototyping. This is important to investigate, as prior work shows that creative concepts from the generation stage tend to be abandoned in favor of more conventional concepts at the selection and final design stages [42]. Furthermore, while prior work emphasizes that something else beyond generating and selecting creative ideas influences creative idea selection [42], this work aims to establish the impact of psychological safety and cognitive style on the paradigm-relatedness of concepts.

Before applying cognitive style to the design stages and individuals' cognitive processes, it is important to understand the inventory used to quantify cognitive style. Particularly, an individual's KAI score falls somewhere within the range of 32 (highly adaptive) to 160 (highly innovative) [10]. When individuals of different KAI scores are placed in a team, diversity between individuals' cognitive styles and/or levels increases and the cognitive gaps grow [28]. Here, it is important to make the distinction between cognitive style and cognitive level. Cognitive style is an individual's stable, characteristic cognitive preference for managing structure in problem solving, while cognitive level describes an individual's cognitive capacity to solve problems and demonstrate creativity. Cognitive level is assessed through measures of both potential capacity (e.g., intelligence and talent) and manifest capacity (e.g., knowledge and skills) [10]. Gaps of 20 points or more can cause conflict in the form of poor communication, blaming one another, and misinterpreting differences in cognitive style as incompetence [28]. Although failing to address conflict could diminish performance, as teams spend more time trying to figure out how to deal with one another, rather than coming up with solutions to the problem itself

[10, 47], coping behavior can mitigate these effects [48]. Specifically, coping behavior is a mechanism used by individuals to deal with the negative impacts of cognitive gap by adjusting one's behavior to solve problems in a way that is not consistent with their preferred style [10]. Such effects of coping behavior on actual problem-solving behavior have been expressed in prior literature, where the context (such as class or team) can impact how individuals manipulate their coping behavior [10, 14, 28]. Results may be further compounded by the by project duration [49] or design task [50] and whether the problem was framed neutrally or not, which can impact novice designers' abilities to respond to a design task [51], as novices tend to not reframe problems [52]. Other forms of team communication can also impact how individuals project their behavior, as some individuals may have a greater impact on team outcomes through being dominating or charismatic, or may not say much at all and conform to group norms [53]. To investigate some of these team dynamics, for example, psychological safety in the manufacturing context was shown to contribute to the ability to engage in divergent thinking, creativity, and risk-taking [54], alluding to association between divergent thinking and cognitive style. Some studies have even pointed to a connection between trust and sharing creative ideas [32], alluding to a link with psychological safety, which is mediated by trust [31].

While coping behavior can help individuals of differing cognitive styles modify their own problem-solving behavior to cooperate better within their teams, there are more effective ways to combat cognitive gap-induced conflict. To mitigate the effects of conflict beyond coping behavior, psychological safety could serve as a factor that influences how teams resolve or ignore conflict. Throughout the engineering design process, conflict can emerge as resistance to externally imposed task commands and interpersonal conflict within the team atmosphere [34]. While we know that conflict can be beneficial for boosting problem-solving performance [55], prior work shows that conflict is beneficial only if team psychological safety is high, allowing team members to speak out against potential issues in a diplomatic manner and overcome fears of being criticized [29, 30]. Importantly, applications outside of engineering design have shown a connection between psychological safety and employees' feelings of vitality and involvement in creative work [56].

3.3.2 Measuring Paradigm Shifting Ideas

In the last few years, the engineering community has made significant strides towards developing new rating methods that allow us to consider ideas on a continuum from incremental to radical [17], fully capturing the ideas behind Thomas Kuhn's pivotal work. Thus, the paradigm-relatedness creativity rating technique was developed within an engineering design context to evaluate design ideas [16, 17]. Specifically, a paradigm refers to the "ways of perceiving or acting in response to a situation or problem," (p. 31), whereas relatedness refers to "the extent that an idea operates within" (p. 31) or challenges that paradigm [17]. The first category used in this technique, paradigm-consistent, describes a solution that resembles an already existing, common design that stays within the problem constraints. The second category, paradigm-challenging, either integrates an uncommon element or relationship into the solution and begins to stretch the problem boundaries. The third and final category, paradigm-breaking, shifts the focus of the problem to a larger problem while violating some or all relevant constraints [17]. Unlike CAT, paradigm-relatedness raters are primed with the problem definition and typical constraints/applications [16, 17] (see [1] for comparison). When using just a category-based approach, this can make it easier to rate larger quantities of ideas with higher interrater reliability [17].

Although the relationship between paradigm-relatedness with KAI scores remains unclear, the foundation of the technique was based on concepts derived from A-I theory [16], which leads us to question how these two variables are related. Thus, the current investigation was developed to explore the role of psychological safety and cognitive style in paradigm-relatedness outputs across the conceptual stages of the engineering design process.

3.3.3 Research Questions

The goal of this paper was to explore the relationship between cognitive style, psychological safety, and the paradigm-relatedness of design outputs as based on ratings from quasi-experts. Specifically, we explored the following research questions (RQs):

RQ1: Can cognitive style and individual perceptions of psychological safety be used to predict the paradigm-relatedness of design solutions that individuals generate?

We hypothesized that higher cognitive style (*innovative* trend) would predict a greater likelihood for paradigm-breaking solutions, whereas lower cognitive style (*adaptive* trend) would predict a greater likelihood for *paradigm-consistent* solutions. This is based on the paradigm-relatedness metric's strong ties to cognitive style [16, 17], where KAI is representative of cognitive style [9, 10]. Consequently, we would expect perceptions of psychological safety to impact whether individuals follow their inherent preferences for generating solutions as based on cognitive style, as psychological safety can promote individuals to voice their ideas and engage in knowledge sharing [30, 33].

RQ2: Can team cognitive style diversity and psychological safety be used to predict the paradigm-relatedness of design solutions that teams select?

We hypothesized that while controlling for cognitive style *elevation* (average) [23], cognitive style *diversity* (standard deviation) [23] (used in prior work in engineering design [13]) would impact the paradigm-relatedness of the percentage of concepts that teams select. This is based on prior work used to develop the paradigm-relatedness scale [16, 17], where cognitive style as defined by KAI [9] was thought to impact the paradigm-relatedness of solutions at the individual level. Thus, aggregating KAI scores to the team level would allow us to depict the *team's* cognitive style, as mean values have been used to represent members' attributes as a collective value [24, 25]. To further describe team attributes through aggregate measures, standard deviation can describe diversity more accurately through controlling for average values [27]. Upon this, we predicted that teams with higher elevation but less diversity to be more likely to choose paradigm-breaking ideas, and teams with lower elevation and less diversity would select paradigm-consistent ideas, as based on the problem-solving tendencies of these individuals [10, 45]. In turn, we would expect that teams with greater cognitive style diversity would select more diverse ideas, as prior work showed that greater cognitive gaps, or differences between individuals in cognitive style [28] can encourage teams to consider a more diverse spread of ideas [10, 28]. However, as teams with greater cognitive style gaps tend to experience conflict [10, 28, 47], team psychological safety could impact how teams navigate their differences. Specifically, higher team psychological safety has encouraged teams to engage in interpersonal risk-taking, speak out against potential issues, and overcome fears of being criticized [29, 30], which can help teams overcome barriers to selecting solutions. Thus, we would expect an interaction between psychological safety and cognitive style diversity.

RQ3: Can the team cognitive style diversity and psychological safety be used to predict the paradigm-relatedness of a team's functional prototype?

We hypothesized that a team's cognitive style *diversity* would predict the likelihood of the paradigm-relatedness of the functional prototype; the final solution. Similar to RQ2, we would expect teams with greater cognitive diversity to be more likely to select a solution that is paradigm-challenging to account for the views of all team members, as these groups tend to explore solutions that span the solution space [10, 28]. Similar to RQ2, controlling for the skew in a team as more adaptive or innovative via cognitive style *elevation* would account for preferences for incremental or innovative improvements, respectively [10, 45]. Although prior work showed that teams with higher levels of cognitive style diversity tended to produce final solutions that outperformed other solutions from teams with lower cognitive diversity [13], how this relates to the paradigm-relatedness of such final designs remains unclear, emphasizing the need to investigate this stage as well. We also hypothesized that higher psychological safety would allow cognitively diverse teams to be more likely to produce functional prototypes that are paradigm-challenging. This would allude to another facet of psychological safety, where team members share a sense of valuing everyone's contributions [29].

3.4 Methodology

To answer the research questions presented above an empirical study was conducted at a large northeastern university over the first project of a cornerstone engineering design course over the Spring of 2019 and 2020, Fall of 2019, and the second summer term of 2018 and 2019. Figure 3.1 depicts the study timeline. These time points were chosen because they represent milestones in the engineering design process for a team [34], and we can extract performance outputs as a result of team interaction for analysis.

3.4.1 Participants

Sixty-nine engineering design student teams, comprised of 263 participants (188 males and 75 females), participated in the study. All participants were enrolled in a first-year cornerstone engineering design class at a large northeastern university. Table 3.1 outlines the participants and their distributions over the data collection periods. The design tasks were further broken down into six (6) categories for analysis with N individuals and M teams (after unreliable data was removed) for each type of analysis: food insecurity (N=43, M=11), air pollution (N=34, M=9), traffic injuries (N=45, M=11), vaccines (N=17, M=3), STEM toys (N=27, M=7), and water transportation/pollution (N=61, M=15), leaving 238 participants split as 222 individuals in 64 teams for RQ1, and 216 individuals in 56 teams for RQ2 and RQ3.

3.4.2 Procedure

The study was completed over the course of five semesters, with eleven sections of a first-year engineering design course, see Table 3.1. Seven of these sections took place over the course of a typical semester, and four occurred over a condensed summer session (see Table 3.1). The course schedule remained consistent across all sections, where the same design outputs were gathered from the same five time points (see Figure 3.1), following the same course schedule presented in [44]. All participants consented at the beginning of the study based on the Institutional Review Board guidelines established at the university. The remainder of this section emphasizes the methodologies used as part of the current investigation, where the psychological safety survey was taken at the end of each time point.

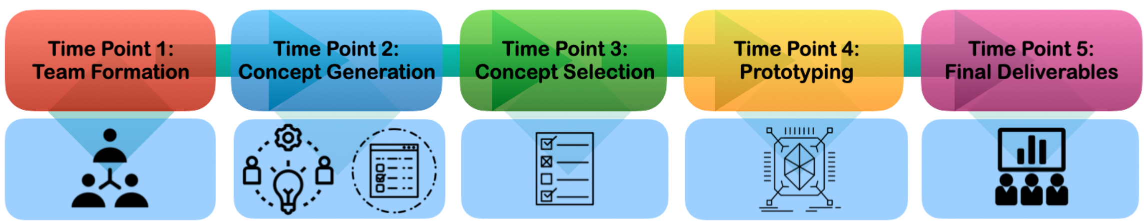


Figure 3.1 Study timeline – Engineering design outputs were gathered at each time point (total time period: 8 weeks for Fall/Spring, 4 weeks for Summer)

After consent was attained, at Time Point 1, participants completed the 32-item KAI inventory to obtain a numerical representation of their cognitive styles—i.e., their individual KAI score. From there, 3- and 4-member teams were formed based on KAI, as in [1]. Next, newly-formed teams were given a design challenge within one of the broad categories presented in Table 3.1 (broken down into the sub-categories in 3.4.1 Participants). Then, teams researched the context of their design problem. During Time Point 2, students attended the same series of lectures in [44], helping them to form their problem statements. Next, the participants engaged in a 15-minute concept generation session with the goal of individually sketching as many ideas as possible. Then, teams joined together to combine their ideas and sketch new ones during a group brainstorming session. At the end the session, the instructor collected the ideas, and digital copies were scanned for analysis. Continuing into the next session at Time Point 3, students followed the same concept screening procedures presented in [44], and were then tasked with selecting three to four of the ideas to prototype, as based on a scoring matrix.

During Time Point 4, students developed low-fidelity prototypes of the ideas they selected. Specifically, they followed the same procedure in [44] when constructing and sharing prototypes. Then, the teams made a functional prototype; a physical model of what they would make for the final deliverable. The individual/team-generated sketches and functional prototypes are shown in Figure 3.2. Finally, during Time Point 5, teams presented their final deliverables, such as their high-fidelity prototypes based on a computer-aided design (CAD) rendering.

Table 3.1 Descriptions of Design Challenges Based on Instructor and Semester

Semester	Instructor	Sample Size (individuals)	Sample Size (teams)	Project Description
Summer 2018*	A	46 students	12 teams	Tackle food insecurity in developing countries as a result of climate, conflict, unstable markets, food waste, and lack of investment in agriculture.
Spring 2019	A and B	49 students	13 teams	Ensure healthy lives and promote the well-being for all at all ages through addressing diseases, pollution, and traffic injuries.
Summer 2019*	A	48 students	12 teams	
Fall 2019	A	32 students	8 teams	
Spring 2020	A and D	58 students	16 teams	
Fall 2019	C	30 students	8 teams	Develop a new water toy for children ages 3 to 5 to teach STEM in a fun, safe, novel way.

*The asterisk represents a semester that was held during a condensed session (4 weeks for project), as opposed to the regular school year semester (8 weeks for project). This difference was controlled for as "regular semester" versus "condensed semester."

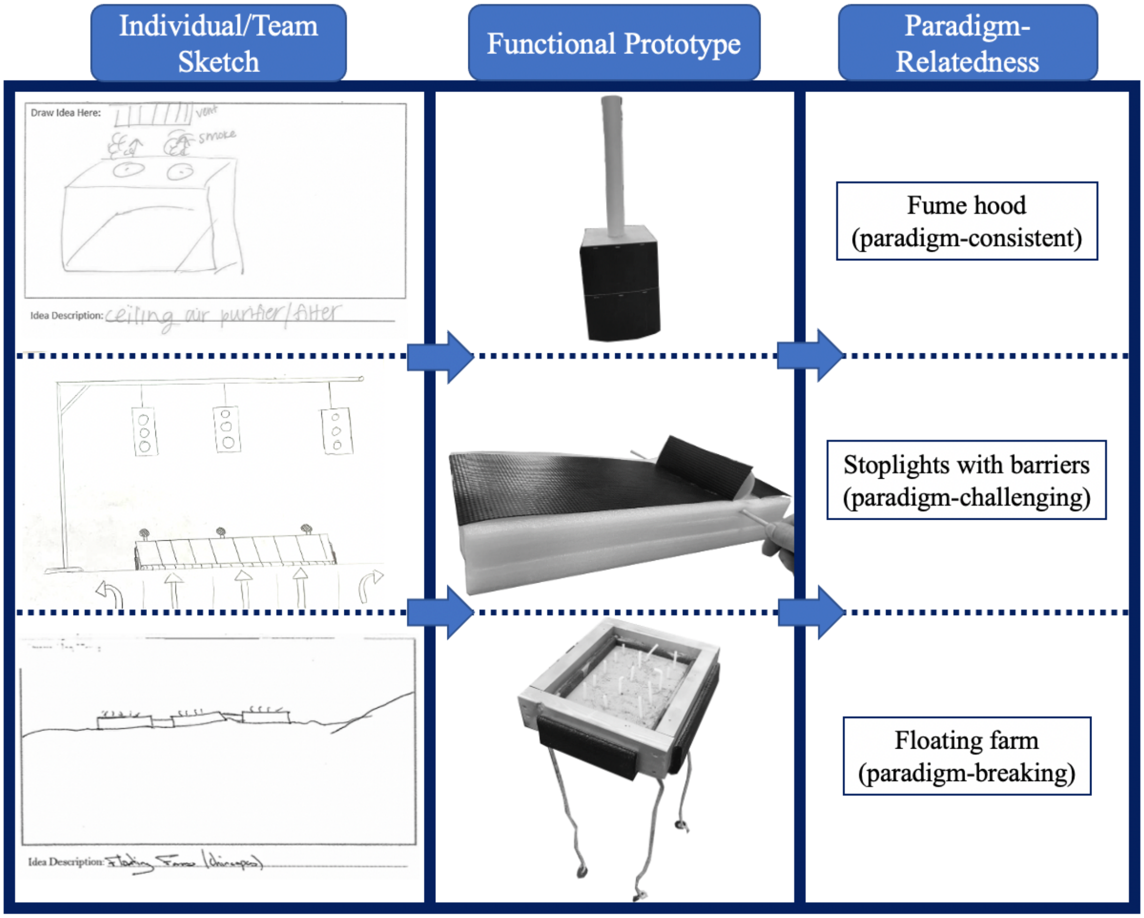


Figure 3.2 Progression of concepts with a representation of each paradigm-relatedness category shows how students designed for air pollution, traffic injuries, and food insecurity.

3.4.3 Design Ratings via Quasi-Experts

After all of the design outputs were compiled from each stage of the design process, Qualtrics surveys similar to the ones in [1] were created, where two quasi-experts; one undergraduate student in mechanical engineering and one Ph.D. student in industrial engineering, rated concepts using paradigm-relatedness [16, 17]. To qualify as quasi-experts, the raters were trained by a metric author. Specifically, the quasi-experts rated 1,654 concepts from the concept generation stage (Time Point 2), 73 additional team-generated ideas, and 69 functional prototypes from the prototyping stage (Time Point 4), which were verified with the CAD models from Time Point 5 as each team's final concept. Additionally, before the functional prototypes were rated, all images were converted to grayscale and a description of the concept was provided. The raters were then tasked with rating the paradigm-relatedness of each concept, as the goal of paradigm-relatedness is to understand how the design itself fits a particular paradigm that either aligns with or defies what would be the typical solution to a given problem [17]. These tasks were the first steps in preparing for the ratings.

To further ensure consistent ratings, both raters established a baseline for each team's problem statement via a list of specific elements and their usages as well as constraints that would be expected for a paradigm-consistent solution. The raters were encouraged to think about the focus of the solution to check whether it addressed the problem at hand or focused on a solution to a larger problem, encompassing the components that the paradigm-relatedness metric utilizes [17]. Quasi-experts primed themselves with these lists before rating ideas, which were randomized within each team. From there, quasi-experts classified each concept into one of three categories: paradigm-consistent, paradigm-challenging, or paradigm-breaking. Using the baseline, concepts were categorized as paradigm-consistent when concepts contained any of the expected elements, paradigm-challenging when containing a combination of expected and unexpected elements, and paradigm-breaking when containing unexpected elements.

After the concepts were rated, reliability of the ratings was checked using a two-way mixed intraclass correlation with absolute agreement. There was a high level of agreement among the quasi-experts for the paradigm-relatedness of the individually generated concepts (ICC(3,2)=0.861), the additional team-generated ideas (ICC(3,2)=0.927) and the functional prototypes (ICC(3,2)=0.871) [57]. Then, quasi-experts generated the final ratings for all concepts as they discussed their differences and collectively assigned values to mismatched ratings.

3.4.4 Data Collection Instruments

During the study, 222 individuals generated an average of 6.17 (SD=2.72) ideas, which were spread out as 512 paradigm-consistent, 393 paradigm-challenging, and 545 paradigm-breaking concepts. From there, teams selected an average of 43.12% (SD=0.22), 34.85% (SD=0.26), and 22.03% (SD=0.24) of paradigm-consistent, paradigm-challenging, and paradigm-breaking concepts, respectively. Of the functional prototypes, teams chose 31 paradigm-consistent, 21 paradigm-challenging, and 4 paradigm-breaking ideas. The remainder of this section presents the results in reference to our research questions. The statistical data were analyzed via the SPSS v.28. A value of $p < .05$ was used to define statistical significance. All assumptions were met unless otherwise noted.

3.4.4.1 Kirton Adaption-Innovation (KAI) Inventory

To measure the impact of cognitive style on the paradigm-relatedness of design solutions from concept generation, the KAI inventory was used to assess problem-solving preferences at both the individual and team level [9]. In this study, the total KAI score, or the sum of the three sub-scores, was used in the analyses. Furthermore, because KAI scores fall on a continuous scale, comparisons of cognitive style are relative, such that lower KAI scores correspond to an individual having a more adaptive cognitive style, whereas individuals with a higher KAI score have a more innovative cognitive style [10]. A certified KAI practitioner collected and scored the student responses at the beginning of each semester that this study was conducted, and the participants received feedback on their results.

The KAI total scores of the 238 engineering design students analyzed across the RQs in this study showed a normal distribution, with the scores ranging from 55 to 127 (M=91.84, SD=13.78), which follow established findings [14].

3.4.4.2 Psychological Safety

To measure psychological safety, or the belief of feeling safe for interpersonal risk taking [29], individual psychological safety scores are computed for each team member from a seven-question, seven-point survey by Edmondson [29] (shown in Appendix B), producing a score from 1 to 7. This individual measure is a perception of the team, whereas the team measure is aggregated as an average at each time point and represents how safe it is to take risks within each team. To ensure consistency across individual responses, interrater agreement must be computed [58]. The calculation for the team psychological safety score is:

$$team\ psychological\ safety_j = \frac{\sum_{i=1}^{K} X_{i,j}}{K} \qquad (1)$$

where $X_{i,j}$ represents the individual psychological safety score of the ith participant on team j, up to K participants on team j.

3.5 Results

During the study, 222 individuals *generated* an average of 6.17 (SD=2.72) ideas, which were spread out as 512 paradigm-consistent, 393 paradigm-challenging, and 545 paradigm-breaking concepts. From there, teams *selected* an average of 43.12% (SD=0.22), 34.85% (SD=0.26), and 22.03% (SD=0.24) of paradigm-consistent, paradigm-challenging, and paradigm-breaking concepts, respectively. Of the functional prototypes, teams chose 31 paradigm-consistent, 21 paradigm-challenging, and 4 paradigm-breaking ideas. The remainder of this section presents the results in reference to our research questions. The statistical data were analyzed via the SPSS v.28. A value of $p < .05$ was used to define statistical significance. All assumptions were met unless otherwise noted.

3.5.1 Can Cognitive Style and Individual Perceptions of Psychological Safety be Used to Predict the Paradigm-Relatedness of Design Solutions that Individuals Generate?

The objective of the first research question was to examine whether KAI scores and perceived psychological safety at Time Point (TP) 2 (concept generation) could be used to predict how ideas would be categorized by paradigm-relatedness ratings at the idea level. Specifically, we hypothesized that KAI scores that reflect a more innovative cognitive style would predict a greater likelihood for paradigm-breaking solutions. Conversely, KAI scores that reflect a more adaptive cognitive style would predict a greater likelihood for paradigm-consistent solutions, as based on paradigm-relatedness's connection with cognitive style [16, 17]. Consequently, we would expect perceptions of psychological safety to impact how individuals utilize preferred problem-solving methods, as psychological safety can promote individuals to share ideas without fear of repercussions [30, 33].

To investigate the influence of cognitive style represented as KAI scores and individual perceptions of psychological safety on this the paradigm-relatedness of concepts individuals generate, a Generalized Estimation Equation (GEE) was generated. Importantly, GEE accounts for clustering effects within groups [59], where concept ratings were clustered within individuals (N=222), which were clustered in teams (N=64), and then in semester duration (N=2); these were specified in the SPSS syntax as within-subject variables to account for clustering. Furthermore, GEE can be used for non-normal, categorical data [59], which represents our dataset. Prior to conducting the analysis, scale validity of the psychological safety scale was validated with Cronbach's $\alpha = 0.715$. Then, all individuals with unreliable KAI scores were excluded, leaving 1,450 ideas. Then, the between-subjects variable was established as participant number multiplied with team number and semester duration (i.e., the interaction) to account for nesting effects, and the within-subjects variable was the number of ideas generated in each paradigm-relatedness category. The reference group for the idea ratings was set to paradigm-consistent, and the reference categories for the categorical factors, design task and semester duration, were set to design task 1 (food insecurity) and the condensed summer session, respectively. These factors were included because design task [50] and project duration [49] have been shown to influence design outputs. We also specified individual KAI scores and individual perceptions of psychological safety as continuous variables. In the first run of the model, interaction effects between design task and individual KAI scores, and individual KAI scores and individual perceptions psychological safety were included, as individuals of certain cognitive styles may be influenced to act within their cognitive style as a result of the given task [51], or feel comfortable (higher psychological safety) to generate ideas as preferred in a team [10], respectively. Results showed an insignificant interaction effect of Design Task and Individual KAI scores ($\chi^2(5) = 7.020$, $p = 0.219$), which was consequently removed from the analysis. However, while insignificant, the interaction between individual KAI scores and psychological safety remained, as this interaction was of interest. The final model showed significant main effects of the Design Task ($\chi^2(5) = 32.948$, $p < 0.001$) on the paradigm-relatedness of design outputs. However, results failed to show a significant interaction effect of individual KAI scores and psychological safety ($\chi^2(1) = 0.05$, $p = 0.822$). Furthermore, there was neither a significant effect of individual KAI ($\chi^2(1) = 0.020$, $p = 0.888$) nor perceived psychological safety scores ($\chi^2(1) = 0.081$, $p = 0.776$). The parameter estimates are summarized in Table 3.2 where all significant parameters are bolded. These estimates represent the level of dependence of paradigm-relatedness ratings on the various independent variables.

Table 3.2 Parameter Estimates for the Paradigm-Relatedness of Concepts Generated by Individuals

Parameter	β	SE_B	χ^2	95% Wald CI	p-value	Odds Ratio
Design Task 1 (food insecurity)	0	-	-	-	-	-
Design Task 2 (air pollution)	**0.809**	**0.2825**	**8.20**	**(.255, 1.362)**	**.004**	**2.246**
Design Task 3 (traffic injuries)	0.295	0.2579	1.311	(-.210, .801)	.252	1.343
Design Task 4 (vaccines)	**1.249**	**0.3172**	**15.497**	**(.627, 1.870)**	**<.001**	**3.486**
Design Task 5 (STEM toys)	**1.269**	**0.3340**	**14.439**	**(.614, 1.924)**	**<.001**	**3.557**
Design Task 6 (water transportation or pollution)	**1.363**	**0.2811**	**23.514**	**(.812, 1.914)**	**<.001**	**3.907**
Condensed Summer Session	0	-	-	-	-	-
Regular Semester	0.021	0.2013	0.010	(-.374, .415)	.918	1.021
Individual KAI	0.005	0.0383	0.020	(-1.078, 1.445)	.888	1.005
Individual Psychological Safety at TP2	0.184	0.6438	0.081	(-1.078, 1.445)	.776	1.202
Individual KAI x Individual Psychological Safety at TP2	0	0.0066	0.050	(-.014, .011)	.822	1

These results did not support our hypothesis, as we expected KAI and psychological safety scores at the individual level to influence the groupings of generated concepts based on paradigm-relatedness. Moreover, the interaction between predictors was insignificant, showing that psychological safety did not promote students to design within their cognitive preferences. While speculative, there may be more to cognitive style in predicting design outputs. For example, prior work found that novice designers (such as the students in our study) are less likely to reframe problems actively [52] and may design under a bias of how the problem was framed, regardless of cognitive style [51]. This suggests that more work is needed to understand the impact of other potential confounding factors in investigating what drives individuals' design outputs. Particularly, the results show a significant relationship between design task and predicting the paradigm-relatedness of generated concepts, aligning with prior work in cognitive style [51]. This means that regardless of an individual's cognitive style, the theme of a design task alone can be enough to encourage particular design outputs. For example, the STEM toy design task (β=1.269) was statistically significant (p = <.001) with an odds ratio of 3.557. This indicates that ideas from individuals who were given the STEM toy task were 3.557 times more likely to be rated as paradigm-challenging or paradigm-breaking than paradigm consistent when compared with the reference group, the food insecurity task.

3.5.2 Can Team Cognitive Style Diversity and Psychological Safety be Used to Predict the Paradigm-Relatedness of Design Solutions that Teams Select?

In addition to what teams decide to generate, we also wanted to see how cognitive style and psychological safety influenced teams' selection processes for prototyping. Specifically, the objective of the second research question was to examine whether cognitive style diversity represented as KAI diversity and psychological safety could be used to predict the percentage of concepts selected for prototyping categorized by paradigm-relatedness ratings at the team level. Similar to RQ1, we hypothesized that higher team cognitive style *diversity* (standard deviation) [23] would impact the paradigm-relatedness of the percentage of concepts that teams select, as based on prior work that highlighted how individuals within teams have preferences for problem-solving [10, 45]. Furthermore, greater cognitive gaps, or differences in cognitive style can encourage teams to consider a more diverse spread of ideas [10, 28]. However, as teams with greater cognitive style gaps tend to experience conflict [10, 28, 47], team psychological safety could impact how team members convey information [29, 30].

To investigate these relationships, we conducted three hierarchical linear regression analyses. The purpose of this was to investigate the paradigm-relatedness of each of the three categories (consistent, challenging, and breaking), and what percentage of the ideas that teams selected belonged to each category. For example, 50% of the ideas a team selects may be paradigm-consistent, whereas the remaining 50% could be divided between paradigm-challenging and paradigm-breaking, adding up to 100%. In the first block, we entered all control variables. Specifically, we controlled for design task and semester duration as categorical variables, and controlled for KAI elevation to avoid confounding with within-group standard deviations [27], as well as the percentage of concepts *generated* per each category (consistent, challenging, and breaking), as the availability of ideas can influence selection [46]. Importantly, the variables for percentage of ideas generated and selected focused on the same paradigm-relatedness category for each analysis. In the second block, we entered KAI diversity and team psychological safety at Time Point 3 as main effects. Finally, to test any interaction effects between KAI diversity and team psychological safety, we computed an interaction effect by multiplying these variables and entered it in the third block. Similar to RQ1, we checked for an interaction effect between design task and KAI diversity in the third block, which showed insignificant interaction effects for all paradigm-relatedness categories ($p > 0.05$). This was consequently removed from the analysis. The results for the final model of each regression analysis can be found in Table 3.3. The remainder of this RQ highlights the findings with respect to each paradigm-relatedness category. Prior to conducting the analyses, scale validity of the psychological safety scale was validated with Cronbach's $\alpha = 0.751$. Then, the validity of team aggregations of psychological safety at *Time Point 3* was verified through interrater agreement calculations ($r_{wg} = 0.87$, ICC(1) = 0.129, ICC(2)=0.354) [58].

For the first analysis, the full model was statistically significant, $R^2 = .342$, $F(11, 44) = 2.083$, $p = .042$; adjusted $R^2 = .178$. Specifically, control variables (design task, semester, and percentage of ideas in each paradigm-relatedness category) in the first block significantly predicted percentage of paradigm-consistent ideas that teams selected, $R^2 = 0.307$, $F(8, 47) = 2.598$, $p = 0.019$; a large effect size. Although still significant overall ($p = .046$), the addition of KAI diversity and team psychological safety at Time Point 3 led to an increase in R^2 of .010, $F(2, 45) = .340$, $p = .714$; a statistically insignificant change. In the third block, the interaction between KAI diversity and psychological safety led to an increase in R^2 of .026, $F(1, 44) = 1.707$, $p = .198$; also not a statistically significant change.

For the second analysis the full model was statistically significant, $R^2 = .383$, $F(11, 44) = 2.485$, $p = .016$; adjusted $R^2 = .229$. Specifically, control variables in the first block significantly predicted percentage of paradigm-challenging ideas that teams selected, $R^2 = 0.378$, $F(8, 47) = 3.574$, $p = 0.003$; a large effect size. Although still significant overall ($p = .009$), the addition of KAI diversity and team psychological safety at Time Point 3 led to an increase in R^2 of .004, $F(2, 45) = .157$, $p = .855$, which was not a statistically significant change. In the third block, the interaction between KAI diversity and psychological safety led to an increase in R^2 of .001, $F(1, 44) = .044$, $p = .834$; also not a statistically significant change.

For the third analysis the full model was statistically significant, $R^2 = .491$, $F(11, 44) = 3.866$, $p < .001$; adjusted $R^2 = .364$. Specifically, control variables in the first block significantly predicted percentage of paradigm-consistent ideas that teams selected, $R^2 = 0.371$, $F(8, 47) = 5.061$, $p < 0.001$; a large effect size. Although still significant overall ($p < .001$), the addition of KAI diversity and team psychological safety at Time Point 3 led to an increase in R^2 of .007, $F(2, 45) = .290$, $p = .750$, which was not a statistically significant change. In the third block, the interaction between KAI diversity and psychological safety led to an increase in R^2 of .022, $F(1, 44) = 1.891$, $p = .176$; also not a statistically significant change.

Table 3.3 Hierarchical Regression Results for the Percentage of Selected Design Solutions Based on Paradigm-Relatedness

	Paradigm-Consistent				Paradigm-Challenging				Paradigm-Breaking			
Predictor	*p*	B	SE_B	$\boldsymbol{\beta}$	*p*	B	SE_B	$\boldsymbol{\beta}$	*p*	B	SE_B	$\boldsymbol{\beta}$
Intercept	0.679	-.399	0.957	-	0.760	0.291	0.947	-	0.690	0.334	0.855	-
Design Task Air Pollution	0.326	0.131	0.132	0.189	0.340	-.123	0.128	-.172	0.952	0.007	0.113	0.010
Traffic Injuries	0.550	0.073	0.122	0.114	0.186	-.162	0.120	-.245	0.292	0.110	0.103	0.178
Vaccines	0.572	0.100	0.176	0.089	0.480	-.119	0.167	-.102	0.791	0.041	0.152	0.037
STEM Toys	0.258	0.172	0.150	0.223	0.116	-.230	0.144	-.290	0.554	0.077	0.129	0.104
Water Transportation or Pollution	0.505	0.087	0.130	0.152	0.353	-.115	0.123	-.194	0.982	0.003	0.123	0.005
Regular Semester	0.590	-.048	0.089	-.091	0.530	0.056	0.088	0.103	0.880	0.011	0.075	0.022
% of Concepts Generated	**.007**	.548	.192	.450	**<.001**	1.101	.253	.576	**<.001**	0.657	0.175	0.608
KAI Elevation	0.764	-.001	0.004	-.039	0.680	-.001	0.004	-.051	0..418	0.002	0.003	0.093
KAI Diversity	0.211	0.080	0.063	2.106	0.865	-.011	0.063	-.272	0.179	-.074	0.055	-2.03
Psychological Safety at TP3	0.468	0.108	0.148	0.195	0.959	-.007	0.146	-.013	0.446	-.097	0.126	-.182
KAI Diversity x Psychological Safety at TP3	0.198	-.013	0.010	-2.20	0.834	0.002	0.010	0.340	0.176	0.012	0.009	2.078
	$R^2 = .342$, $p = .042$				$R^2=.383$, $p = .016$				$R^2=.491$, $p < .001$			

Note: Food insecurity and the condensed summer session were used as reference categories for design task and semester, respectively. All significant predictors' values are in **BOLD**.

These results failed to support our hypothesis, as neither psychological safety nor KAI diversity statistically significantly contributed to the model. In fact, the percentage of ideas available in each paradigm-relatedness category was the main driver in predicting the percentage of concepts that teams select. This aligns with prior work, where the ideas to be selected were contingent on the availability of generated solutions [36]. Our results indicate that other mechanisms beyond the team's cognitive style diversity may play a role in decision-making processes for selecting ideas, such as coping behavior [10]. However, psychological safety alone was not enough to capture this behavior, establishing the need for exploring what factors contribute to how teams select ideas.

3.5.3 Can Team Cognitive Style Diversity and Psychological Safety be Used to Predict the Paradigm-Relatedness of a Team's Functional Prototype?

Focusing on the remaining design stages, the objective of the third research question was to determine how KAI scores psychological safety could be used to predict how functional prototypes (which were prototypes for the final designs) would be categorized by paradigm-relatedness ratings at the team level. Specifically, we hypothesized that a team's cognitive style *diversity* would predict the likelihood of the paradigm-relatedness of the functional prototype, where we would expect teams with greater cognitive diversity to be more likely to select a solution that is paradigm-challenging to account for the views of all team members [10, 28]. We also hypothesized that higher psychological safety would contribute to cognitively diverse teams' actions, as psychological safety promotes teams to value others' contributions [29].

To investigate this relationship, we conducted a multinominal logistic regression to model the relationship between the team's KAI elevation (mean), KAI diversity (standard deviation), team psychological safety at Time Point 4 (prototyping), design task, semester duration, and the classification of concepts of the functional prototypes into the three paradigms (paradigm-consistent, paradigm-challenging, paradigm-breaking). Importantly, scale validity of the psychological safety scale was validated with Cronbach's $\alpha = 0.746$.

Then, validity of team aggregations of psychological safety at *Time Point 4* was verified through interrater agreement calculations (r_{wg} = 0.91, ICC(1) = 0.090, ICC(2)=0.269) [58]. Similar to RQ2, KAI elevation was included to account for confounding effects with KAI diversity, and we validated that both variables were not correlated (r(54) = -.076, p = .580). Addition of the predictors (KAI diversity, elevation, team psychological safety, design task, and semester duration) to the model that contained only the intercept significantly improved the fit between model and data, χ^2 (18, N=56) = 29.248, Nagelkerke R^2 = .491, p = .045. Significant unique contributions were made by the diversity of KAI scores (χ^2 (2) = 7.267, p = .02). The parameter estimates are shown in Table 3.4.

Table 3.4 Predictors' Unique Contributions in the Multinomial Logistic Regression for Psychological Safety and KAI

	Predictor	Consistent Vs.	β	Odds Ratio	p
Design Task	Air Pollution	Challenging	-1.914	0.147	0.163
		Breaking	-16.268	<.001	0.999
	Traffic Injuries	Challenging	-.170	0.844	0.897
		Breaking	1.397	4.042	0.586
	Vaccines	Challenging	-2.347	0.096	0.152
		Breaking	-16.485	<.001	0.999
	STEM Toys	Challenging	-3.115	0.044	0.060
		Breaking	-20.466	<.001	0.999
	Water Transportation or Pollution	Challenging	-1.857	0.156	0.128
		Breaking	0.156	<.001	0.997
	Regular Semester	Challenging	0.039	1.040	0.967
		Breaking	-4.033	0.018	0.216
	KAI Elevation	Challenging	0.066	1.068	0.118
		Breaking	0.157	1.170	0.363
	KAI Diversity	Challenging	.095	1.100	0.077
		Breaking	0.347	1.415	0.080
	Psychological Safety at TP4	Challenging	-.271	0.762	0.752
		Breaking	1.547	4.696	0.393

Note: Food insecurity and the condensed summer session were used as reference categories for design task and semester, respectively.

Similar to RQ1, the reference group for the dependent variable was the paradigm-consistent category. Each predictor had two parameters that was compared with the reference category: one for predicting membership in the paradigm-challenging group paradigm-breaking, and one for predicting membership in the paradigm-breaking group. Although the parameters for comparing the paradigm-consistent with both paradigm-challenging (p = .077) and paradigm-breaking (p = .080) groups did not quite meet statistical significance, it is important to discuss the meaning of odds ratios. Specifically, for each unit of increase in KAI diversity, the odds of being in the paradigm-challenging group compared to the paradigm-consistent group increased by 1.10. Similarly, the odds of being in the paradigm-breaking group compared to the paradigm consistent group increased by 1.415. However, the odds ratios should be interpreted conservatively.

These results supported our hypothesis to an extent, as teams' cognitive gaps increased (cognitive style diversity [13]), teams gravitated towards more paradigm-challenging and paradigm-breaking designs, aligning with expectations from prior work [10, 28]. However, lack of significance of psychological safety in the model showed that psychological safety was not necessarily impactful on the paradigm-relatedness of teams' functional prototypes. Similar to RQ2, this indicated that interactions that impact how teams make a collective decision cannot be captured with psychological safety alone.

3.6 Discussion

The main objective of this paper was to explore the role of cognitive style (using the KAI metric) on the paradigm-relatedness of design outputs from various design stages at the individual and team levels. The main findings were as follows:

- Only design task significantly predicted the likelihood of individuals to *generate* more paradigm-challenging or paradigm-breaking ideas than paradigm-consistent.
- The availability of ideas in each of the paradigm-relatedness categories significantly predicted teams selecting a similar ratio of ideas for each category.
- KAI diversity was a significant predictor for the teams selecting more paradigm-challenging and paradigm-breaking functional prototype concepts compared to paradigm-consistent.
- Psychological safety at the individual and team levels was not significant, and thus was not enough to capture team interactions that impact team decision-making.

Results from the first research question refuted our hypothesis, as neither KAI nor perceptions of psychological safety contributed the model for predicting the paradigm-relatedness of ideas. Specifically, controlling for design task was statistically significant, where the air pollution, vaccine, STEM toy, and water pollution/transportation tasks were more likely to elicit paradigm-challenging or paradigm-breaking outputs than paradigm-consistent outputs. Although this finding aligns with prior work [50], recent work on cognitive style pointed to a potential confounding factor within design task—problem framing [51]. Because problem framing left unmanaged could misalign with a novice's preferred cognitive style [51], concept generation outputs may be at risk, particularly when individuals on teams with varied cognitive styles must interpret the same problem statement. Typically, novice designers tend to solve problems as given [52], where our participants were novices as well and would be less likely to reframe a potentially biased problem statement, regardless of cognitive style. Another confounding factor within design task could come from varying degrees of background knowledge of the design problem [37], which could limit more innovative individuals' abilities to produce more paradigm-challenging and paradigm-breaking concepts. We hypothesized that higher perceptions of psychological safety would allow individuals generate concepts according to their cognitive style through avoiding coping behavior as a means of handling conflict [10] and feeling safe to engage in creative processes [54]. However, lack of tacit knowledge for some individuals may be too significant, preventing them from engaging in creative behavior. Thus, these results call for future work that dives deeper into the intricacies of design task to better understand how KAI can be used to predict concept generation outputs.

While the paradigm-relatedness of individual ideation outputs showed a significant relationship with design task, results from team-level analyses in the second and third research questions showed insignificant to limited impacts of KAI diversity on paradigm-relatedness outputs. Specifically, RQ2 showed that neither KAI diversity nor psychological safety significantly impacted teams' selections of which concepts would move forward to the prototyping stage. The availability of concepts alone contributed to the model for the percentage of surviving concepts in each paradigm-relatedness category, showing that the kinds of concepts that survive are contingent on what team members produce during concept generation, aligning with prior work [36]. Lack of significance from KAI measures could be confounded in factors similar to RQ1, such as background knowledge of the design problem [37], where some team members who have a better understanding of the problem may contribute more to the decision. Specifically, contributions across the team may be unequal as some individuals have more power in advocating for their preferred decision [53], meaning that team decisions on the surface may come from one or two people. Conversely, KAI diversity was significant overall for predicting the paradigm-relatedness of functional prototypes, alluding to greater representation of team attributes than in the selection stage. This aligned with prior work, where greater cognitive gaps from differences in cognitive style can encourage teams to consider a more diverse spread of ideas [10, 28], and consequently a more divergent final design. The significance of this finding establishes directions for future work, as KAI diversity could detect the likelihood of the paradigm-relatedness of team outputs only until teams chose their final designs. This finding suggests that the relationship between KAI and the paradigm-relatedness of design outputs takes time to emerge, and KAI measures may be confounded in other factors in the earlier stages.

Contrasting with the emerging significance of KAI diversity, both team-level analyses showed lack of influence from psychological safety. Specifically, we expected psychological safety to allow teams to act according to their cognitive style composition when selecting concepts, as the construct promotes team members to share concerns and speak up [29, 30]. However, lack of significance could be due to the scale's inability to capture coping behavior, where team members force themselves to problem-solve outside of their defined cognitive style [10]. Furthermore, this work focused on the paradigm-relatedness of design outputs, which is not the same as conventional creativity [18]. This could explain the lack of a relationship between psychological safety and design outputs here, as prior work with psychological safety focused exclusively on creativity as a matter of being creative or not [32, 33]. All ideas categorized under the paradigm-relatedness metric are considered creative [16, 17], where the innovativeness or adaptiveness can vary. Thus, caution should be taken when trying to compare newer metrics with psychological safety, as prior work analyzed psychological safety under an antiquated definition of creativity.

3.7 Conclusions and Future Work

The main goal of this paper was to investigate the relationship between cognitive style, psychological safety, and the paradigm-relatedness of design outputs during the *concept generation*, *concept selection*, and *prototyping* stages of the design process. Specifically, we sought to understand this impact at both the individual and team level. To achieve this goal, we investigated design outputs from 238 participants split between various stages. The main findings indicated that design task and the availability of generated concepts were impactful on the paradigm-relatedness of design outputs at concept generation and concept selection, respectively. Conversely, only cognitive style diversity was impactful on the functional prototypes, and psychological safety was not significantly impactful at all stages.

While this study presents results to broaden our view of what factors impact the paradigm-relatedness of design outputs at various stages, this paper does not come without limitations. First, many factors can influence what kinds of ideas individuals propose during concept generation, such as tacit knowledge about the design task [37] or engaging in coping behavior [10]. Although psychological safety was measured to capture individual perceptions of feeling safe to take risks (e.g., producing more innovative solutions) within teams [29, 30], this does not necessarily capture coping behavior, which can push more adaptive individuals to produce more innovative outputs, and vice versa [10]. Furthermore, coping behavior can mitigate effects of conflict due to interpersonal conflict [48], which may drive design processes more than psychological safety. Therefore, future work should incorporate measures that explicitly capture coping behavior.

In addition to the need for capturing coping behavior, other interpersonal interactions could contribute to what factors drive decision-making processes when selecting concepts. Although additive aggregation models including KAI elevation and diversity assume that all team members' scores should be equally represented (e.g., [26]), some members may exert a disproportional influence on team design processes. Specifically, some individuals may have a greater impact on team outcomes through dominating the conversation, persuasively advocating for their idea (e.g., ownership bias), or demonstrating charismatic leadership (e.g., [53]). In contrast, some individuals may have a lower impact on team outcomes through failing to speak up, quickly acquiescing to others' ideas, or conforming to the majority decision even if they hold an alternative opinion [53]. The effects of how coping behavior leads individuals to change their behavior depending on the context have been examined in prior literature [10, 14, 28], emphasizing the need for further exploration when investigating the paradigm-relatedness of design outputs.

Beyond the potential for coping behavior to overshadow impacts from other factors, the lack of significance from psychological safety could be due to several reasons. First, the construct requires a significant amount of interaction and manifests over time [30]. Thus, the duration of the projects may be too short to capture the impacts of psychological safety, but may be more noticeable in longer projects, such as semester- or year-long capstone projects. Along with confounding due to project duration, impacts from individual perceptions of psychological safety may go undetected. Specifically for the team-level analyses, the positive skew in psychological safety in the team-level aggregate scores may conceal lower individual perceptions of psychological safety, as highlighted in prior work [25] and in engineering design [44]. Therefore, future work should examine individual-level perceptions of psychological safety and how they impact individual contributions within team design activities.

Aside from limitations with capturing coping behavior and psychological safety, results showed that cognitive style diversity represented via KAI diversity was impactful only when investigating functional prototypes. Furthermore, these impacts were less nuanced when viewed as pairwise comparisons between paradigm-relatedness categories. While prior work showed that more "creative" concepts tended to drop out in favor of more conventional concepts in the later stages of the design process [42], our findings showed that predicting the likelihood for teams to select unorthodox concepts was more apparent than in previous stages. Particularly, this work did not investigate how teams' pools of ideas survived across the design stages, but rather indicated KAI's relevance at later stages of the design project. Furthermore, this study did not investigate prototype fidelity (such as the low-fidelity prototypes), which can cause more breaking ideas to drop out through enhanced perceptions of riskiness [41]. To develop a better understanding of the survival of concepts under a cognitive style lens, investigating both individual- and team-level design decision-making processes simultaneously could illustrate to what extent cognitive style can predict design outcomes. Finally, the loss of data from unreliable KAI scores could have masked some of the interactions in teams that contributed to design outputs, as well as not including instructor as a control (omitted due to too many predictors affecting model validity). However, such impacts are most likely minimal, especially from the perspective of instructor, where outputs were not graded.

3.8 References

[1] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2021, "The Crowd Predicts a Paradigm Shift: Exploring the Relationship Between Cognitive Style and the Paradigm-Relatedness of Design Solutions," Proc. ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[2] Kuhn, T. S., 1962, The structure of scientific revolutions, Chicago, University of Chicago Press.
[3] Merriam-Webster, "Paradigm shift," Merriam-Webster.com dictionary.
[4] Norman, D. A., and Verganti, R., 2014, "Incremental and radical innovation: Design research vs. technology and meaning change," Design Issues, 30(1), pp. 78-96.
[5] Crilly, N., 2010, "The structure of design revolutions: Kuhnian paradigm shifts in creative problem solving," Design issues, 26(1), pp. 54-66.
[6] Farrell, R., and Hooker, C., 2013, "Design, science and wicked problems," Design Studies, 34(6), pp. 681-705.
[7] Rittel, H. W. J., and Webber, M. M., 1973, "Dilemmas in a general theory of planning," Policy Sciences, 4(2), pp. 155-169.
[8] Brush, S. G., 2000, "Thomas Kuhn as a Historian of Science," Science & Education, 9(1), pp. 39-58.
[9] Kirton, M., 1976, "Adaptors and innovators: A description and measure," Journal of Applied Psychology, 61(5), pp. 622-629.

[10] Kirton, M. J., 2011, Adaption-Innovation in the Context of Diversity and Change, Routledge, London, UK.
[11] Kirton, M. J., 1984, "Adaptors and innovators—Why new initiatives get blocked," Long Range Planning, 17(2), pp. 137-143.
[12] Jablokow, K. W., 2008, "Developing problem solving leadership: A cognitive approach," International Journal of Engineering Education, 24(5), pp. 936-954.
[13] Menold, J., and Jablokow, K., 2019, "Exploring the effects of cognitive style diversity and self-efficacy beliefs on final design attributes in student design teams," Design Studies, 60, pp. 71-102.
[14] Jablokow, K. W., Teerlink, W., Yilmaz, S., Daly, S. R., and Silk, E. M., 2015, "The Impact of Teaming and Cognitive Style on Student Perceptions of Design Ideation Outcomes," ASEE Conferences, Seattle, Washington.
[15] Heininger, K., Chen, H.-E., Jablokow, K., and Miller, S. R., "How Engineering Design Students' Creative Preferences and Cognitive Styles Impact Their Concept Generation and Screening," Proc. ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[16] Silk, E. M., Daly, S. R., Jablokow, K. W., Yilmaz, S., Rechkemmer, A., and Wenger, J. M., "Using paradigm-relatedness to measure design ideation shifts," Proc. American Society for Engineering Education (ASEE) Annual Conference.
[17] Silk, E. M., Daly, S. R., Jablokow, K. W., and McKilligan, S., 2019, "Incremental to radical ideas: paradigm-relatedness metrics for investigating ideation creativity and diversity," International Journal of Design Creativity and Innovation, 7(1-2), pp. 30-49.
[18] Nagasundaram, M., and Bostrom, R. P., 1994, "The Structuring of Creative Processes Using GSS: A Framework for Research," Journal of Management Information Systems, 11(3), pp. 87-114.
[19] Dean, D. L., Hender, J., Rodgers, T., and Santanen, E., 2006, "Identifying good ideas: constructs and scales for idea evaluation," Journal of Association for Information Systems, 7(10), pp. 646-699.
[20] Paulus, P. B., and Brown, V. R., 2007, "Toward More Creative and Innovative Group Idea Generation: A Cognitive-Social-Motivational Perspective of Brainstorming," Social and Personality Psychology Compass, 1(1), pp. 248-265.
[21] Nijstad, B. A., and De Dreu, C. K. W., 2002, "Creativity and Group Innovation," Applied Psychology, 51(3), pp. 400-406.
[22] Fairchild, J., and Hunter, S. T., 2014, ""We've Got Creative Differences": The Effects of Task Conflict and Participative Safety on Team Creative Performance," The Journal of Creative Behavior, 48(1), pp. 64-87.
[23] Neuman, G. A., Wagner, S. H., and Christiansen, N. D., 1999, "The Relationship between Work-Team Personality Composition and the Job Performance of Teams," Group & Organization Management, 24(1), pp. 28-45.
[24] Mathieu, J., Maynard, M. T., Rapp, T., and Gilson, L., 2008, "Team effectiveness 1997-2007: A review of recent advancements and a glimpse into the future," Journal of management, 34(3), pp. 410-476.

[25] Mathieu, J. E., Gallagher, P. T., Domingo, M. A., and Klock, E. A., 2019, "Embracing Complexity: Reviewing the Past Decade of Team Effectiveness Research," Annual Review of Organizational Psychology and Organizational Behavior, 6(1), pp. 17-46.
[26] Van der Vegt, G. S., de Jong, S. B., Bunderson, J. S., and Molleman, E., 2010, "Power Asymmetry and Learning in Teams: The Moderating Role of Performance Feedback," Organization Science, 21(2), pp. 347-361.
[27] Harrison, D. A., and Klein, K. J., 2007, "What's the difference? Diversity constructs as separation, variety, or disparity in organizations," Academy of Management Review, 32(4), pp. 1199-1228.
[28] Jablokow, K. W., and Booth, D. E., 2006, "The impact and management of cognitive gap in high performance product development organizations," Journal of Engineering and Technology Management, 23(4), pp. 313-336.
[29] Edmondson, A., 1999, "Psychological safety and learning behavior in work teams," Administrative science quarterly, 44(2), pp. 350-383.
[30] Edmondson, A. C., and Lei, Z., 2014, "Psychological Safety: The History, Renaissance, and Future of an Interpersonal Construct," Annual Review of Organizational Psychology and Organizational Behavior, 1(1), pp. 23-43.
[31] Conchie, S. M., Donald, I. J., and Taylor, P. J., 2006, "Trust: Missing Piece(s) in the Safety Puzzle," Risk Analysis, 26(5), pp. 1097-1104.
[32] Gong, Y., Cheung, S.-Y., Wang, M., and Huang, J.-C., 2012, "Unfolding the Proactive Process for Creativity:Integration of the Employee Proactivity, Information Exchange, and Psychological Safety Perspectives," Journal of Management, 38(5), pp. 1611-1633.
[33] Kessel, M., Kratzer, J., and Schultz, C., 2012, "Psychological Safety, Knowledge Sharing, and Creative Performance in Healthcare Teams," Creativity and Innovation Management, 21(2), pp. 147-157.
[34] Dym, C. L., and Little, P., 2014, Engineering design: A project-based introduction, John Wiley and sons.
[35] Amabile, T. M., 1988, "A model of creativity and innovation in organizations," Research in organizational behavior, 10(1), pp. 123-167.
[36] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2006, "Productivity is not enough: A comparison of interactive and nominal brainstorming groups on idea generation and selection," Journal of Experimental Social Psychology, 42(2), pp. 244-251.
[37] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2007, "Relative accessibility of domain knowledge and creativity: The effects of knowledge activation on the quantity and originality of generated ideas," Journal of Experimental Social Psychology, 43(6), pp. 933-946.
[38] Cooper, R. G., and De Brentani, U., 1984, "Criteria for screening new industrial products," Industrial Marketing Management, 13(3), pp. 149-156.
[39] Zheng, X., Ritter, S. C., and Miller, S. R., 2018, "How Concept Selection Tools Impact the Development of Creative Ideas in Engineering Design Education," Journal of Mechanical Design, 140(5).
[40] Kolodner, J. L., and Wills, L. M., 1996, "Powers of observation in creative design," Design Studies, 17(4), pp. 385-416.

[41] Starkey, E. M., Menold, J., and Miller, S. R., 2019, "When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk," Journal of Mechanical Design, 141(3).
[42] Starkey, E., Toh, C. A., and Miller, S. R., 2016, "Abandoning creativity: The evolution of creative ideas in engineering design course projects," Design Studies, 47, pp. 47-72.
[43] Toh, C. A., and Miller, S. R., 2015, "How engineering teams select design concepts: A view through the lens of creativity," Design Studies, 38, pp. 111-138.
[44] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., "How Engineering Design Students' Psychological Safety Impacts Team Concept Generation and Screening Practices," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[45] Jablokow, K. W., and Kirton, M. J., 2009, Problem solving, creativity, and the level-style distinction, Springer, New York.
[46] Toh, C. A., and Miller, S. R., 2016, "Choosing creativity: the role of individual risk and ambiguity aversion on creative concept selection in engineering design," Research in Engineering Design, 27(3), pp. 195-219.
[47] Buffinton, K. W., Jablokow, K. W., and Martin, K. A., 2002, "Project Team Dynamics and Cognitive Style," Engineering Management Journal, 14(3), pp. 25-33.
[48] Clapp, R. G., and De Ciantis, S. M., 1989, "Adaptors and Innovators in Large Organizations: Does Cognitive Style Characterize Actual Behavior of Employees at Work? An Exploratory Study," Psychological Reports, 65(2), pp. 503-513.
[49] Hassannezhad, M., Cantamessa, M., Montagna, F., and Clarkson, P. J., 2019, "Managing Sociotechnical Complexity in Engineering Design Projects," Journal of Mechanical Design, 141(8).
[50] Tekmen-Araci, Y., and Mann, L., 2019, "Instructor approaches to creativity in engineering design education," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233(2), pp. 395-402.
[51] Silk, E. M., Rechkemmer, A. E., Daly, S. R., Jablokow, K. W., and McKilligan, S., 2021, "Problem framing and cognitive style: Impacts on design ideation perceptions," Design Studies, 74, p. 101015.
[52] Crismond, D. P., and Adams, R. S., 2012, "The Informed Design Teaching and Learning Matrix," Journal of Engineering Education, 101(4), pp. 738-797.
[53] Mathieu, J. E., Tannenbaum, S. I., Donsbach, J. S., and Alliger, G. M., 2014, "A Review and Integration of Team Composition Models:Moving Toward a Dynamic and Temporal Framework," Journal of Management, 40(1), pp. 130-160.
[54] Choo, A. S., Linderman, K., and Schroeder, R. G., 2007, "Social and Method Effects on Learning Behaviors and Knowledge Creation in Six Sigma Projects," Manag. Sci., 53(3), pp. 437-450.
[55] Jonassen, D. H., and Cho, Y. H., 2011, "Fostering Argumentation While Solving Engineering Ethics Problems," Journal of Engineering Education, 100(4), pp. 680-702.
[56] Kark, R., and Carmeli, A., 2009, "Alive and creating: the mediating role of vitality and aliveness in the relationship between psychological safety and creative work involvement," Journal of Organizational Behavior, 30(6), pp. 785-804.

[57] Shrout, P. E., and Fleiss, J. L., 1979, "Intraclass correlations: Uses in assessing rater reliability," Psychological Bulletin, 86(2), pp. 420-428.
[58] LeBreton, J. M., and Senter, J. L., 2008, "Answers to 20 Questions About Interrater Reliability and Interrater Agreement," Organizational Research Methods, 11(4), pp. 815-852.
[59] Galbraith, S., Daniel, J. A., and Vissel, B., 2010, "A Study of Clustered Data and Approaches to Its Analysis," The Journal of Neuroscience, 30(32), pp. 10601-10608.

CHAPTER 4

THE IMPACT OF GENDER ON INDIVIDUAL PERCEPTIONS AND TEAM PSYCHOLOGICAL SAFETY IN ENGINEERING DESIGN TEAMS

This paper is based on a conference paper previously published in the International Design Engineering Technical Conference and Computers and Information in Engineering Conference [1]. This paper was invited to be submitted for publication in a special issue of the Journal of Mechanical Design in August 2022. This work is multiple-authored by Courtney Cole, Jacqueline Marhefka, Dr. Kathryn Jablokow, Dr. Susan Simkins, Dr. Sarah Ritter, and Dr. Scarlett Miller. Courtney Cole is the lead author on the paper, and Dr. Scarlett Miller and Dr. Kathryn Jablokow helped advise the work.

In Chapters 2 and 3 of this dissertation, findings identified the extent to which psychological safety can be used to predict design outputs at various stages of the engineering design process. After establishing the connection between psychological safety and design outputs, Chapter 4 looked to identify a relationship with antecedents to psychological safety using gender. Specifically, individual dichotomous perceptions, as well as the gender composition of the teams were investigated to understand how this surface-level diversity can be used to predict psychological safety. Through understanding gender as a means to influence individuals' and teams' psychological safety, this chapter aimed to establish a baseline for investigating other team attributes that may impact psychological safety, eventually helping to pave the way for using psychological safety in promoting various design outputs.

4.1 Abstract

Improving team interactions in engineering to model gender inclusivity has been at the forefront of many initiatives in both academia and industry. However, there has been limited evidence on the impact of gender-diverse teams on psychological safety. This is important because psychological safety has been shown to be a key facet for the development of innovative ideas, and has also been shown to be a cornerstone of effective teamwork. But how does the gender diversity of a team impact the development of psychological safety? The current study was developed to explore just this through an empirical study with 38 engineering design student teams over the course of an 8-week design project. These teams were designed to be half heterogeneous (either half-male and half-female, or majority male) or other half homogeneous (all male). We captured psychological safety at five time points between the homogenous and heterogenous teams and also explored individual dichotomous (peer-review) ratings of psychological safety at the end of the project. Results indicated that there was no difference in psychological safety between gender homogenous and heterogenous teams. However, females perceived themselves as more psychologically safe with other female team members compared to their ratings of male team members. Females also perceived themselves to be less psychologically safe with male team members compared to male ratings of female team members, indicating a discrepancy in perceptions between genders. These results point to the need to further explore the role of minoritized groups in psychological safety research and to explore how this effect presents itself (or is covered up) at the team level.

4.2 Introduction

In recent years, understanding how to increase retention of women in engineering has been at the forefront of many academic [2-6] and industry-based [7-9] initiatives. Importantly, initiatives have spanned to including other genders as well to promote greater inclusion in the male-dominated field that is engineering [10-12]. While these initiatives are important from the perspective of perceived learning gains among diverse individuals that work together [13], how to promote safe environments for communication in gender-diverse teams remains a challenge.

To address this challenge, recent work in engineering design education has looked at increasing team effectiveness from the perspective of psychological safety [14, 15]. Importantly, psychological safety is defined as "the shared belief that the team is safe for interpersonal risk taking," ([16] p. 354). While outside of engineering, psychological safety has been validated as a consistent, generalizable, and multilevel predictor of team performance and learning [17]. To build a culture of safety, individuals engage in interpersonal interactions that develop from perceptions of one another to group-level phenomenon [18, 19]. It's important to note that these feelings of safety have been shown to grow and diminish throughout the lifespan of a team [17], pointing to impacts on group processes [20, 21]. This emphasizes the need for a dynamic view of psychological safety in teams.

While recent work has begun to examine psychological safety from a dynamic perspective in engineering design [14, 15, 22, 23], examinations of gender-based interactions in engineering design have seen limited treatment from a single time point [24]. In other instances, studies on gender and individual perceptions of psychological safety showed conflicting results, where some studies found that controlling for gender did not impact results [25, 26], but others found quite the opposite [27, 28]. Furthermore, studies in business teams focused showed that gender diversity shared a positive relationship with psychological safety [29]. Conversely, prior work in engineering design education found that team psychological safety did not vary between teams of varying gender compositions [24]. These discrepancies can be due to any number of reasons, calling to attention the need for a more detailed view of psychological safety and gender. Thus, this begs the question as to *when* in the design process that gender composition has an impact on individual perceptions and team psychological safety. For the purposes of the literature review, we use *nonmale* to refer to both female and nonmale. However, we use *female* to describe our results, as the nonmale sample was fully female.

In light of the prior work, the objective of this paper was to explore the relationship between gender and psychological safety throughout the design process. Specifically, we sought to understand this relationship at both the individual level through pairwise perceptions of psychological safety. In addition, we sought to understand this relationship at the team level through comparisons of two combinations of team gender composition over time. Furthermore, we looked at whether team gender composition contributed to improvements in psychological safety from the start of the project to the end.

4.3 Related Work

To identify specific points in the engineering design process where team gender composition may impact team psychological safety (and while not the focus of this chapter, the proceeding design outputs), pertinent literature on the impacts of gender on team psychological safety in various contexts was explored. Furthermore, studies on gender and its impacts on team interactions in and outside engineering were explored. This section is used to summarize this prior work and provide support for the current investigation.

4.3.1 Potential Impacts of Team Gender Composition on Team Interactions

Although what drives gender-based differences in engineering design team interactions under a psychological safety lens remains sparse, other works provide a means for studying these factors throughout the design process. Outside of engineering, gender diversity shared a positive relationship with psychological safety in industry settings [29, 30], alluding to the importance of studying psychological safety in an engineering context. Specifically, prior work on gender interactions in teams has shown that members in single-gender teams tend to employ aggressive tactics [31], where evolutionary psychology points to males in particular for having a stronger desire to compete for status and exhibit dysfunctional behaviors that promote group hostility [32]. Conversely, mixed gender teams tend to stray away from engaging in hostile behavior [33], suggesting that such negative interactions are less likely to occur in mixed gender teams. This is problematic for achieving high psychological safety, as hostile environments can be perceived as not psychologically safe [34]. When studying team gender composition under a STEM lens, conclusions from prior work showed that while women still remain underrepresented, gender composition from the perspectives of homogeneous and heterogeneous groups showed support for enhancing group processes and performance in general [35]. Interestingly, other work in science further supports this notion, as heterogeneous gender teams tended to produce publications with higher performance (quantified by citation count) than their homogeneous counterparts [36]. However, due to the extreme underrepresentation of nonmales in engineering [37], it is less common for teams to be homogeneously nonmale. As a result, comparing homogeneously male teams to mixed gender through giving participants to identify as a gender other than cisgender would help to change the paradigm of how researchers view gender composition in STEM.

As nonmales continue to experience underrepresentation, the lack of knowledge on engineering teams is problematic. Particularly, prior work from the perspective of engineering teams showed that male dominant teams tended to engage in more clarifying and standard-setting during team interactions [38]. However, how these interactions impact psychological safety lacks emphasis in the engineering design literature. Prior work in problem-based learning in engineering education showed that some individuals may perceive members of genders different from their own to be a challenge for working in teams or may refuse to work with these individuals [39]. These interactions help to explain why nonmale engineers still face adversity, where females in a workplace setting have been judged negatively by their gender at first [40], and only until recently has there been a push to examine impacts on other genders [11]. Additionally, females in majority-female groups report feeling less anxious than when on minority teams [41], alluding to the notion that females can give other females strength in male-dominated fields such as engineering. However, even in gender-balanced groups, prior work showed that females are more likely to assume non-technical, traditional female roles that involve secretarial work, while males assume more technical roles [42], which may negatively impact how team members perceive one another and themselves due to lack of appreciation for non-technical skills [42, 43]. Other factors can build into these interactions as well, such as gender status beliefs, which have imposed burdens on minoritized genders that leave males better off [44, 45]. Although outside engineering, lower psychological safety in females in healthcare has been shown to be indicative of status issues as a result of gender [46]. Discrimination can be further compounded if an individual comes from a minoritized group, where qualitative studies have shown that being both female and multi-minority can complicate how welcome such individuals feel in engineering, especially when interacting with other non-minority individuals [47, 48]. Interestingly, both minority and White females expressed experience with microaggressions from non-minority individuals, where the effects were especially elevated for minority women [49]. While not the focus of this paper, work with the same participants aimed to improve psychological safety through role-based assignments and video-based training from the beginning of the project [50, 51]. Importantly, prior work advocates for assigning roles and rotating roles to ensure equity among minority groups in STEM [52], whereas video-based education can be an effective method for changing individuals' behavior and how they interact with others [53, 54]. Although these studies leave out psychological safety as a component of what helps or hinders performance in these individuals, such findings point to a discrepancy in how underrepresentation of certain genders in general can lead to frustrations among these groups. Thus, these prior works emphasize the need for a better understanding of how team gender composition relates to psychological safety in the engineering design process.

4.3.2 Potential Impacts of Gender Throughout the Engineering Design Process

In general, the engineering design process is encompassed by three main phases: generation of concepts, evaluation of concepts, and team communication [55, 56]. Prior to generation, however, teams undergo team formation, where they establish a sense of leadership, norms, and culture [57-60]. This can set the stage for the lifespan of the project, where prior work showed that ensuring team members are given an active role in decision-making and taking on tasks suitable for their abilities can affect overall team performance [61, 62]. Additionally, leaders can play a role in establishing norms, as prior work showed how higher expectations from the leader can positively impact team and individual norms for collaborative problem solving in a classroom setting [63]. However, in the engineering design team context, prior work suggested that a shared sense of project ownership and shared team leadership is necessary for project success [64]. For nonmales in engineering, this is a critical time period, as prior work in engineering suggests that females in their first year of undergraduate education may lack the confidence needed to provide contributions at the beginning of a project [38]. Although outside of engineering design, controlling for gender diversity was not found to significantly impact the positive relationship between psychological safety and collective leadership that builds over time, including the beginning of a project [65]. At the individual level, similar findings showed lack of a relationship between individual perceptions of the team's psychological safety and gender at the beginning of data collection [66, 67]. However, how long these team members were working with each other prior to the study, or which team they were in was not explicitly stated. Similarly, investigations in the engineering design context remain limited, as prior work showed only a static view of the impacts of gender [24]. Lack of clarity in how gender can influence psychological safety is problematic, as these studies fail to describe the trajectory of psychological safety over time from the individual (gender to gender) and team levels (team gender composition). Particularly in engineering design, to overcome gender-related issues such as the reluctance to contribute, it is important to identify clearly as to how psychological safety may play a role promoting team members to help individuals and teams share a similar sense of leadership and belonging from the start.

After establishing team norms, engineering design teams collectively work towards their established problem during the concept generation stage. Here, teams are tasked with developing creative solutions; a common focus in engineering design [68-72]. In prior work, teams with lower psychological safety were shown to feel unsafe for interpersonal risk-taking, causing individuals within the teams to feel reluctant to share novel ideas [73]. Similarly, feeling safe to speak up and learn from mistakes has also been shown to promote creative behavior in teams [74-76]. Interestingly, prior work in business teams found an indirect relationship between status conflict and team creativity via team psychological safety [29]. Specifically, greater gender diversity mitigated the negative effects of status conflicts that harm creative outputs, demonstrating the relevance of studying gender composition in our own engineering design teams. However, even in a mixed-gender team, females tend to require a more positive social interaction culture than males before they feel safe to engage in knowledge sharing [77]; an output of psychological safety [16, 17]. As knowledge sharing plays a role in allowing design teams to develop new concepts [78], investigating psychological safety remains a crucial first step for improving generation practices.

Following generation practices, teams screen and select ideas to move forward with pursuing [55]. Here, risk aversion is a prominent obstacle for teams to overcome when selecting creative ideas [79, 80]. Importantly, because lower psychological safety can promote greater risk aversion [16], and females are more likely to be affected by risk aversion [81], investigating how gender impacts psychological safety at this stage is important as well. From there, teams transform these concepts into prototypes of varying levels of fidelity to convey their design [82-85] and detect potential design issues [86]. Prototyping shares some similarities with concept screening as well, where prior research showed that engineering design students tend to perceive more unique ideas as riskier if the fidelity is lower [87]. Consequently, psychological safety may compound the outcome of overlooking potentially successful ideas if they do not feel safe for risk-taking [16, 17]. Gender composition could further impact such outcomes due to the aforementioned risk aversion [81], substantiating the importance of studying gender's impact on psychological safety during prototyping.

After deciding on and building the final prototype, teams compile their work as a final deliverable to demonstrate how they solved their design problem. This end stage can be affected by poor communication, which can promote interpersonal tension and irritation [17], and lack of time management [14]. In the case of low psychological safety, such issues can fester if team members do not feel safe to question the status quo [16]. Particularly, prior work shows that females in an engineering team typically assume more stereotypical roles, such as the communicator or planner [45]. However, males tend to dominate more in the presence of females and control team conversations [42, 88, 89]. This can be problematic for nonmales wanting to take part in team decisions, lowering perceptions of psychological safety through making them feel less important [16]. As a result, lack of ability to coordinate and come together could be plagued by low psychological safety, emphasizing its importance even at the end of a project.

While findings from prior work provide a foundation for why gender may impact psychological safety in engineering design teams, evidence remains limited within engineering design. Therefore, this calls for an investigation of how gender from the perspectives of peer ratings and teams can impact individual perceptions of and team psychological safety, respectively.

4.3.3 Research Questions

The goal of this paper was to explore the relationship between gender and psychological safety throughout the engineering design process. Specifically, the following research questions (RQs) were explored:

RQ1: How does gender impact individuals' perceptions of psychological safety with other team members?

We hypothesized a team member's perception of their psychological safety with another individual whose gender does not match their own will be different from individuals who share the same gender. This hypothesis is based on prior work that has shown that females perceive biases from male counterparts in feeling negatively judged based on their gender [40] and feeling less anxious on female-majority engineering teams [41]. Furthermore, knowledge sharing, which is mediated by psychological safety [16, 17], has been shown to require more positive social interaction culture from females than males to feel safe to engage in knowledge sharing [77]. Through facing similar challenges in adversity [40], we predict that members of the same gender orientation will be more likely to feel more psychologically safe with one another.

RQ2: What is the impact of team gender composition on psychological safety over time?

We hypothesized that over a trajectory of time, a team's gender composition will impact *team* psychological safety throughout the design process. Specifically, we hypothesized that mixed gender teams (gender heterogeneous) would have higher psychological safety than teams that are all male (gender homogeneous). This hypothesis is based on prior work that showed that teams of company employees with more gender-diverse teams reported higher psychological safety [29], while other work supports the notion of higher performance outputs from heterogeneous gender groups [35]. Furthermore, while prior work in engineering education shows lack of a difference between teams of varying gender composition [24], this study only analyzed psychological safety from a single point in time. As prior work shows that the trajectory of psychological safety for an engineering design team can vary over time between teams [14], this emphasizes the need to analyze how gender composition impacts the trajectory explicitly.

RQ3: Does the gender composition of a team impact psychological safety by the end of a project?

Building onto RQ2, we aimed to investigate if team gender composition contributed to a difference in psychological safety from the start to the end of the project. Specifically, we hypothesized that mixed gender composition teams' (gender heterogeneous) psychological safety would differ from all male teams (gender homogeneous). This hypothesis is based on prior work that showed that psychological safety is lower when gender diversity is lower [29, 30], and that psychological safety tends to suffer even more in the presence of conflict [29]. Importantly, prior work emphasized how males in general tend to approach interpersonal problems through aggression when there is lack of agreement [31]. However, mixed gender teams tended to stray from using hostile actions and words [33], creating a climate more conducive for overcoming problems and building psychological safety [75]. Starting from the team formation stage (Time Point 1), we predicted that teams of heterogeneous team gender compositions will exhibit greater psychological safety at the end of the project (Time Point 5) than the homogeneous teams.

4.4 Methodology

To answer the research questions, an empirical study was conducted at a large northeastern university in the United States over the first project of a first-year cornerstone engineering design course over five semesters. Further study details and the experimental design are presented in the remainder of this section.

4.4.1 Participants

In total, 38 engineering design student teams, comprised of 148 participants (121 males and 27 females), participated in the study. All participants were enrolled in a first-year cornerstone engineering design class at a large northeastern university. Table 4.1 shows the breakdown of individual gender and racial backgrounds. Table 4.2 shows gender and racial background of teams, the where minoritized members in STEM excludes majority races such as White and Asian [48]. Importantly, all participants were given the option to identify as transgender male/female, genderqueer/non-conforming, or a different identity. However, none of the participants identified as a gender besides the cisgender categories. Therefore, our nonmale sample was fully female and is referred to as such throughout the remainder of this paper. Finally, racial background was not investigated due to the overwhelming Whiteness of the sample size.

4.4.2 Procedure

This study was completed during the Fall 2021 semester with six sections of the same course. The course schedule remained consistent across all sections, where the all participants took the psychological safety survey by Edmondson [16] at each of the time points (see Figure 4.1). All participants consented at the beginning of the study based on the Institutional Review Board guidelines established at the university. The remainder of this section emphasizes the methodologies used to deploy the intervention.

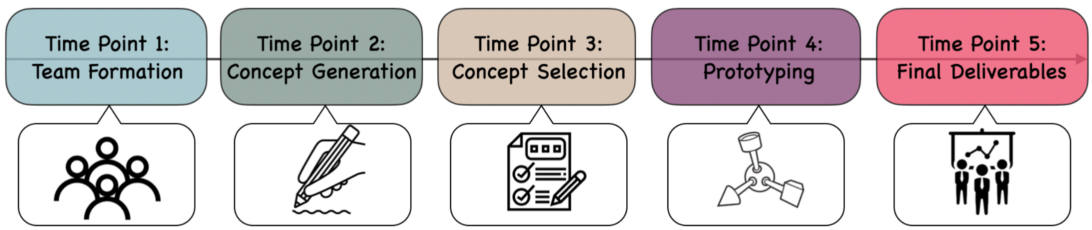


Figure 4.1 Study timeline – all participants took the psychological safety survey at each time point (total time period: 8 weeks).

After consent was obtained, all students completed a psychological safety knowledge self-efficacy presurvey at Time Point 1. These questions focused on being able to explain psychological safety to a peer, being able to state why and when it is important, and being able to identify factors that impact psychological safety, for example. Specifically, one of the items was, "I can describe to a peer what psychological safety is." From there, 3- and 4-member teams were formed to come up with a roughly equal distribution of gender compositions within each class. Specifically, approximately half of the teams were constructed as gender heterogeneous (either half-male and half-female, or majority male), while the other half were constructed as homogeneous (all male). At the beginning of first session the teams spent together, the teams watched the first video in the series of videos on the four lenses of psychological safety. Specifically, these lenses were: Turn-Taking Equalizer, Creativity Promoter, Point of View Shifter, and Affirmation Advocate, which are presented in detail in [51]. The purpose of these roles was to encourage students to take specific viewpoints that promote stronger communication and explore the problem space. Prior to the start of working on the main project, all teams in the intervention condition worked on building a paper bridge as a team-building activity. Here, each participant in each team was assigned a role as based on the lenses of psychological safety, as described in the video. Then, instructors assigned a design challenge to each of the newly-formed teams, where teams researched the context of their design problem for approximately 35 minutes. Importantly, sections in the previous studies [14, 15] were assigned the same research task as well. Following this, all students took the first psychological safety survey.

During Time Point 2, all sections were presented with the same series of lectures in [15] that led up to teams generating problem statement for their project. Importantly, sections under the intervention condition watched the second video on the psychological safety lenses, which focused on concept generation. Then, the participants sketched as many ideas as possible individually in a 15-minute concept generation session. From there, using the same roles described before, each student was assigned a role different from what they did during the first time point. Next, the participants discussed the ideas they generated in their teams and sketched additional solutions as a team. After this, all students took the second psychological safety survey.

During Time Point 3, watched the third video on the psychological safety lenses, which was related to concept screening and how to use the roles to foster communication. From there, students followed a concept screening activity, where they screened the ideas from concept generation. The ideas were mixed up randomly to avoid any ordering biases, where students screened ideas as “Consider” or “Do Not Consider,” similar to [14, 15]. From there, the teams discussed the ideas using the role assignments and decided on which of the four ideas they would rate in more detail. To assess these ideas, students attended a presentation on using concept selection matrices, and then applied this method to rate the ideas they selected. Finally, all students took the third psychological safety survey.

At Time Point 4, students watched the fourth and final video on the psychological safety lenses. Specifically, this video focused on how to apply each role for the remainder of the project. From there, the students watched a brief presentation on low-fidelity prototypes, and were then tasked with making their own prototypes as a team while using commonly available materials (e.g., cardboard, post-it notes, etc.). After they finished the prototypes, students split from their teams while each student took one of the prototypes to share with another group for feedback. After this period, students decided on their final design for the functional prototype and worked together to make this higher fidelity prototype. After this, the students took the fourth psychological safety survey.

At Time Point 5, the project ended with students presenting their final deliverables as a team and turning in the final report. Specifically, these deliverables focused students explaining their design process that led up to the high-fidelity prototype based on a computer-aided design (CAD) rendering. Then, they completed the final psychological safety survey, along with peer reviews and the same psychological safety knowledge self-efficacy survey from the beginning of the study.

4.4.3 Metrics

To investigate the impact of gender on teams' psychological safety, several metrics were applied, including: individual gender-to-gender peer ratings of perceived psychological safety, team psychological safety, and team gender composition. Each metric is defined in detail in the remainder of this section.

Individual Dichotomous Perceptions of Psychological Safety: At the individual level, psychological safety is a perception of the individual's view of how safe they feel the team atmosphere is for interpersonal risk-taking [16]. To uncover feelings of being safe for interpersonal risk-taking with another individual within the team, participants were asked the same psychological safety questions from Edmondson [16] with respect to each of their team members at the final time point. From there, these responses were categorized under four groups to capture dichotomous perceptions of psychological safety based on a member of a particular gender rating another individual of some gender. Specifically, males were included as the dominant gender, whereas females and other minority genders were included under the "nonmale" category. However, our sample reflected just females in this category, thus we will refer to this minoritized group as such. Using the dichotomous structure, psychological safety scores fell into one of four categories: male perceives male, male perceives female, female perceives male, and female perceives male. An example of how these perceptions were coded is shown in Figure 4.2.

Team Psychological Safety: Psychological safety at the team level, or the team's belief of feeling safe for interpersonal risk taking [16], is computed from individual psychological safety scores of each team member and aggregated as an average at each time point. To ensure consistency across individual responses such that all team members share similar perceptions, interrater agreement must be computed [90]. The score ranges from 1 to 7 and is a continuous value, and is calculated as such:

$$team\,psychological\,safety_j = \frac{\sum_{i=1}^{K} X_{i,j}}{K} \qquad (1)$$

where $X_{i,j}$ represents the individual psychological safety score of the ith participant on team j, up to K participants on team j.

Team Gender Composition: To investigate psychological safety at the team level, a team's gender composition was either categorized as gender homogeneous (in this case, all males) or gender heterogeneous (at least one participant was female). This metric is based on how team gender composition was analyzed under two groups in prior work [35, 36] in various contexts including STEM. In an engineering context, females remain underrepresented [37], thus this viewpoint allows us to compare historically dominant all-male teams to mixed teams.

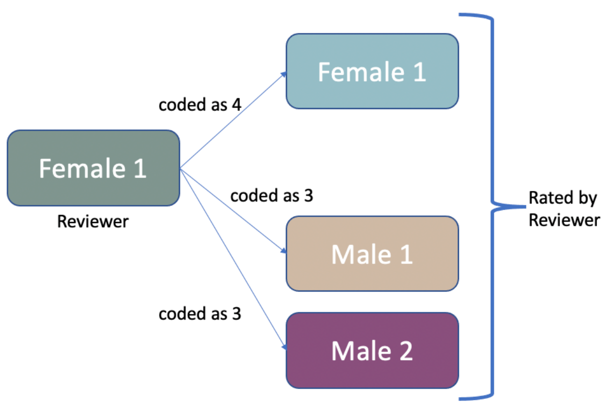


Figure 4.2 Example of how gender-based perceptions were coded. All individual ratings were nested within teams.

4.5 Results

Thirty-eight (38) teams comprised of 148 participants (121 males and 27 females) were included in the analysis. Of these teams, 19 were homogeneous and 19 were heterogeneous in terms of their gender composition. Over all time points investigated, homogeneous and heterogeneous teams' average psychological safety scores were 6.15 (SD=0.596) and 6.17 (SD=0.522), respectively. The remainder of this section presents the results in reference to our research questions. The statistical data were analyzed via SPSS v.28. A value of $p < .05$ was used to define statistical significance [91]. Prior to the analyses, the validity of team aggregations of psychological safety at each of the time points were verified, similar to prior work [14, 15]. Specifically, Cronbach's alpha was calculated as the first step to ensure scale validity [92], where values ranged from 0.70 to 0.82 for the team perceptions, and 0.77 for the peer evaluations at Time Point 5. Then, interrater agreement calculations revealed an acceptable level of agreement at the five time points, with mean r_{wg} ranging from 0.79 to 0.93, ICC(1) ranging from 0.03 to 0.25, and ICC(2) ranging from 0.10 to 0.51 [90]. The acceptability is based on the criteria defined in LeBreton and Senter (2008) [90], where our ICC(1) estimates are, for the most part, medium to large effect sizes, and the r_{wg} values indicate strong agreement. The remainder of this section presents the main results of this study.

4.5.1 RQ1: How does gender impact individuals' perceptions of psychological safety with other team members?

The objective of our first research question was to examine if a team member's perception of their psychological safety with a team member of a different gender differed from members of the same gender. To answer this research question, 361 ratings of perceived psychological safety was analyzed across the 38 teams. We hypothesized that team members' psychological safety ratings of individuals whose gender did not match their own would be different from individuals who shared the same gender. This hypothesis was based on prior work that has shown that females tend to feel negatively judged by their male counterparts based on their gender [40] and feel less anxious in female-majority engineering teams [41]. Through enduring similar challenges together [40], we also predicted that female participants would have higher levels of perceived psychologically safe with other female team members compared to male team members. See Table 4.1 and Table 4.2 for the demographic breakdown.

Table 4.1 Descriptive statistics of individuals based on gender and racial background

Team Gender Composition	***N***	***Team Racial Background Composition***	***N***
0 Females	19	*0 minoritized members*	26
1 Females	11	*1 minoritized member*	11
2 Females	8	*2 minoritized members*	1
3 Females	0	*3 minoritized members*	0

Note: N represents the number of teams that have a specified number of females on their team (0 females=all male). M represents the number of teams with minoritized individuals in STEM, or individuals who do not identify as White or Asian (0 minoritized members=all White and/or Asian).

Table 4.2 Descriptive statistics of teams based on gender and racial background

Individual Gender Count	***N***	***Individual Racial Count***	***M***
Male	121	*White*	102
Female	27	*Black*	7
Transgender Male/Female	0	*Asian*	24
Non-cisgender	0	*Native American*	1
		Multiracial	5
		Prefer Not to Say	9

Note: N represents the number of individuals that identified as a particular gender, whereas M represents the racial background of these individuals that they identified with.

To test these hypotheses, a nested ANOVA was conducted to examine the main effects of individual gender-based perceptions, team membership, and individual gender-based perceptions nested within teams on dichotomous perceptions of psychological safety.

Specifically, individual gender-based perceptions refers to when a team member of a specific gender *perceives* how psychologically safe they feel with another team member of some gender. The groups were classified into four groups with the following group sizes, unweighted marginal means, and standard deviations: male perceptions of males (n=242, M=6.50, SD=0.652), male perceptions of females (n=49, M=6.71, SD=0.441), female perceptions of males (n=55, M=6.31, SD=0.826), and female perceptions of females (n=15, M=6.84, SD=0.119), see Figure 4.3 for a graph of these differences.

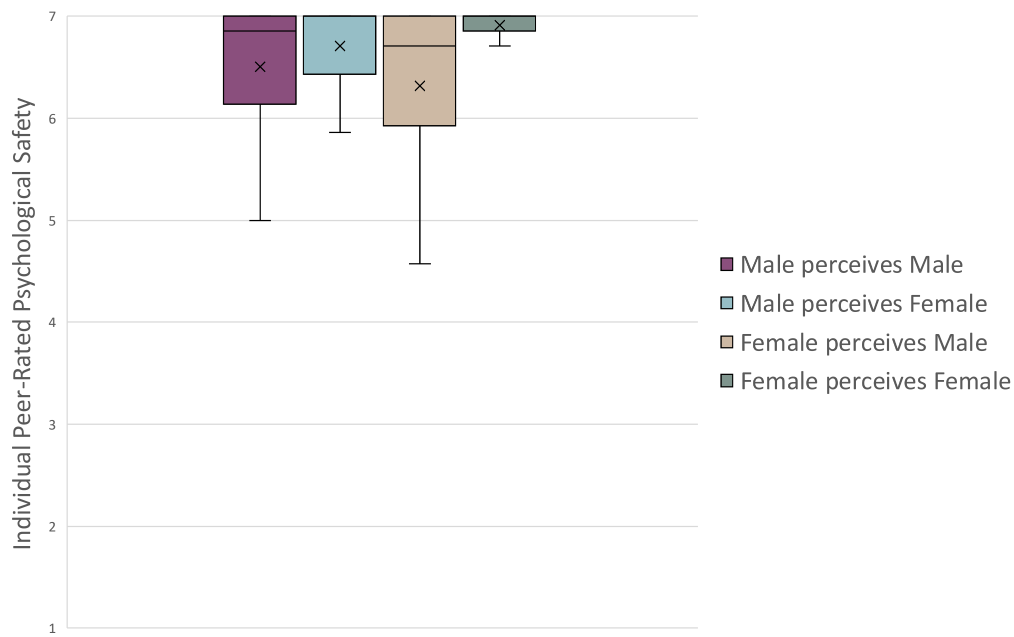


Figure 4.3 Average individual peer-rated psychological safety scores for each gender combination, $F(3, 283) = 6.260$, $p < 0.001$. X on the graph represents the mean for each category.

Prior to the analysis, assumptions were checked. Specifically, outliers were assessed by inspection of a boxplot, and the few outliers were transformed into less extreme values. Data was not normally distributed for each group, as assessed by the Shapiro-Wilk test ($p < .001$), and homogeneity of variances was violated, as assessed by Levene's Test of Homogeneity of Variance ($p < .001$). Because the nested ANOVA is robust to deviations from normality and homogeneity [93], the analysis proceeded as planned.

The results of the nested ANOVA showed that there was a statistically significant main effect of dichotomous individual perceptions of psychological safety, $F(3, 283) =$

6.260, $p < 0.001$, partial $\eta^2 = .062$. Additionally, there was a statistically significant main effect of the teams themselves, $F(37, 283) = 2.676$, $p < 0.001$, partial $\eta^2 = .259$. This showed that teams' psychological safety scores varied significantly in comparison to each other. However, there were no significant main effects of dichotomous individual perceptions of psychological safety nested within teams, $F(37, 283) = 1.272$, $p = .144$, partial $\eta^2 = .143$. This conveyed that team membership did not have a significant impact on dichotomous perceptions of psychological safety. All pairwise comparisons were computed with 95% confidence intervals and Bonferroni-adjusted *p*-values. The results showed that female participant perceptions of psychological safety with other female team members was higher by 0.5971 points, 95% CI [0.1434, 1.051] compared to their perceptions of a male team member ($p = .003$). Additionally, female team member perceptions of a male team member were associated with a lower psychological safety by 0.3949 points, 95% CI [-.7009, -.0890] compared to males perceived psychological safety with a female team member ($p = .004$).

These results support our hypothesis that gender would influence dichotomous individual perceptions of psychological safety. Specifically, females found themselves to feel less psychologically safe with males than they do with other females. This aligns with prior work that showed females to feel less anxious around other females in engineering [41], alluding to the idea that females tend to feel greater support when working with a minoritized gender such as themselves. Interestingly, females feel less psychologically safe with males than males feel with females, further supporting the notion that females in engineering have more intensified feelings of discomfort than males face when interacting with females. This can be attributed to the greater presence of males, as males do not face the same adversity that females would encounter [40, 42]. In fact, males' perceptions of other males compared to perceptions of females were not significantly different. This further substantiates that females are more at risk for lower perceptions of psychological safety in engineering teams. Taken together, these findings imply that to increase psychological safety within an engineering design team, placing two females on a team together can allow these individuals to empower one another to feel psychologically safe.

4.5.2 RQ2: What is the impact of team gender composition on psychological safety over time?

The objective of our second research question was to examine how team gender composition impacts team psychological safety over five time points in the engineering design process. Specifically, we hypothesized that mixed gender teams (gender heterogeneous), that contained at least one female, would have higher psychological safety than teams that were all male (gender homogeneous). This hypothesis was based on prior work that showed that individuals reported higher psychological safety in more gender-diverse teams [29]. Furthermore, mixed gender teams have been shown to stray away from engaging in hostile behavior [33], suggesting that the negative interactions that could break down psychological safety are less likely to occur in mixed gender teams.

To answer this question, we generated a repeated measures mixed linear model (LMM), with team gender composition and the time points in the engineering design process as fixed effects, and class section and team number as random effects using diagonal components covariance. This model was used over other simplified models to account for non-independence in the data (see [94] for full explanation), where the outcome (psychological safety) was measured more than once on the same teams split among multiple class sections. Additionally, random effects allow us to generalize the findings to other engineering design teams and classrooms using random effects, similar to prior work in engineering education [95]. Importantly, aggregations to the team level were supported by scale validity and interrater agreement values, presented in beginning of the "Results and Discussion" section.

To compute this, we first ran the full model while accounting for an interaction effect between gender composition and the time points. This analysis failed to show statistical significance, $F(4, 47.844) = .465$, $p = 0.761$, and was removed. After removing the interaction effect, results indicated that there was no significant main effect of team gender composition on team psychological safety scores, $F(1, 34.704) = .002$, $p = 0.968$, Cohen's d=0.0438. However, the main effect of the time points was statistically significant, $F(4, 48.725) = 11.174$, $p < 0.001$. Specifically, estimates of fixed effects showed that there was a significance mean difference with higher psychological safety at Time Point 5 than Time Point 1, M= 0.468, 95% CI [0.306, 0.631], $p < .001$, Cohen's d = 0.650. Similarly, there was a significance mean difference with higher psychological safety at Time Point 5 than Time Point 2, M= 0.31, 95% CI [0.164, 0.456], $p < .001$, Cohen's d = 0.308. A graph of these differences is shown in Figure 4.4.

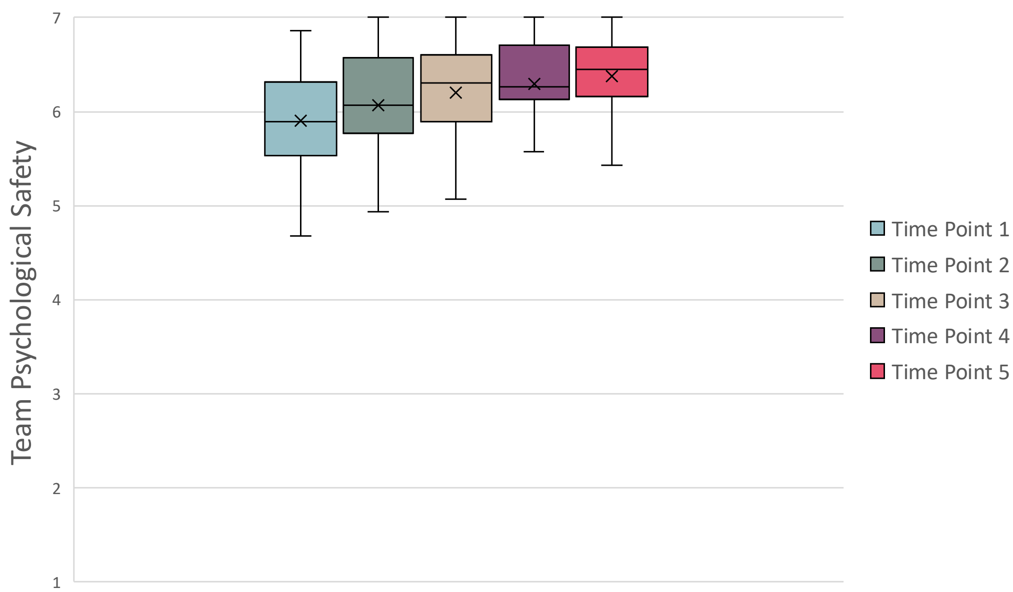


Figure 4.4 Average team psychological safety scores at each time point, $F(4, 48.725) = 11.174$, $p < 0.001$. X on the graph represents the mean for each category.

These results refuted our hypothesis, as team gender composition was not shown to contribute to differences in team psychological safety. While prior work suggests that interactions in mixed gender teams tend to be less hostile and aggressive than single gender teams [32, 33], where hostile environments can be perceived as not psychologically safe [34], that was not the case here. However, results did show psychological safety to be statistically significantly different over time, regardless of gender composition. Specifically, psychological safety was highest at the end of the project (Time Point 5), and was significantly higher than teams' psychological safety at the team formation (Time Point 1) and concept generation (Time Point 2) stages. While not explicitly related to gender, this indicates that teams in the earlier stages of the design process could be subject to lower psychological safety. This could impact how teams establish norms at the beginning of the project, impacting the entire lifespan of a project [57-60]. Furthermore, generation processes could be at risk as well, as lower psychological safety could impair teams' capabilities to engage in creative behavior [76-78]. However, while these differences may seem concerning, the increase in psychological safety is actually beneficial. Thus, we can assume that team members can become more psychologically safety with each other over time, and not the other way around.

4.5.3 RQ3: Does the gender composition of a team impact psychological safety by the end of a project?

The objective of our final research question was to investigate how team gender composition impacted psychological safety by the end of the project. Specifically, we hypothesized that teams of mixed gender composition (gender heterogeneous) would have different psychological safety scores compared to all male teams (gender homogeneous). This hypothesis was based on prior work that showed that psychological safety is lower when gender diversity is lower [29, 30]. Particularly, the link between psychological safety suffering due to unmanageable conflict [29] could be associated with negative interactions that are characteristic of certain genders. For example, prior work emphasized how in general, males on a team tend to approach interpersonal problems through aggression when there is lack of agreement [31]. However, mixed gender teams tended to stray from using hostile actions and words [33], creating a climate more conducive for managing issues and building psychological safety [75].

To answer this question, an ANCOVA was run to determine the effect of homogeneous and heterogeneous team gender compositions on team psychological safety at Time Point 5 after controlling for team psychological safety at Time Point 1. Prior to conducting the analysis, scale validity was validated for Time Points 1 (α=0.75) and 5 (α=0.70). From there, interrater agreement was also validated for Time Points 1 (ICC(1)=0.154, ICC(2)=0.38, mean r_{wg}=0.89) and 5 (ICC(1)=0.092, ICC(2)=0.268, mean r_{wg}=0.90). Unadjusted means are presented, unless otherwise stated.

Table 4.3 Adjusted and Unadjusted Means and Variability for Psychological Safety (PS) at Time Point 5 with Time Point 1 PS as a Covariate

		Unadjusted		*Adjusted*	
	N	*M*	*SD*	*M*	*SE*
Gender Homogenous	19	6.46	.352	6.46	0.87
Gender Heterogenous	19	6.33	.466	6.32	0.87

The results showed that team psychological safety was greater in gender homogeneous teams (M = 6.46, SD = 0.352) compared to the gender heterogeneous teams (M = 6.33, SD = 0.466) (see Table 4.3, where N=number of teams, M=mean, SD=standard deviation, and SE=standard error). Of the heterogeneous teams, 11 had one female and 8 had two females. Prior to conducting the analysis, several assumptions were verified. First, we determined that there was a linear relationship between Time Point 1 and Time Point 5 team psychological safety scores for both gender homogeneous and heterogeneous groups, as assessed by visual inspection of a scatterplot. Also, there was homogeneity of regression slopes as the interaction term was not statistically significant, $F(1, 34) = .139, p = .711$. Standardized residuals for the gender groups were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). Additionally, standardized residuals for the overall model were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). There was homoscedasticity, as assessed by visual inspection of the standardized residuals plotted against the predicted values, and there was homogeneity of variances, as assessed by Levene's test of homogeneity of variance ($p = .288$). Finally, there were no outliers in the data, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for team psychological safety at Time Point 1, results failed to show a statistically significant difference in team psychological safety at Time Point 5 between the two gender composition types, $F(1, 35) = 1.206, p = .280$, Cohen's d = .343.

These results did not support our hypothesis, as team gender composition did not impact whether teams' psychological safety changed by the end of the project. Although prior work showed that psychological safety tends to be lower when gender diversity is low [29, 30], such differences between the teams were not apparent here. These results convey that there are factors beyond team gender composition, such as the environment (education versus industry) that can influence psychological safety by the end of a project.

4.6 Discussion

The main objective of this paper was to explore the relationship between gender and psychological safety throughout the design process at the individual and team levels. The main findings of this study were as follows:

- Females perceive themselves as being less psychologically safe with males than males perceive themselves with females.
- Females perceive themselves as less psychologically safe with males than they do with other females.
- Team gender composition was not shown to significantly impact psychological safety over time, although psychological safety did significantly vary when comparing both Time Point 1 and 2 to 5.
- Psychological safety did not change significantly under the influence of team gender composition at the end of the project.

To understand the implications of these findings, we provided a discussion on each of the main analyses. Specifically, results from the first research question indicated that while constructing teams as all-male or mixed gender (one or two females) does not necessarily elicit differences in psychological safety, individual dichotomous perceptions of psychological safety were significantly impacted by gender. The finding that females had lower perceptions of psychological safety complements prior work that found that females felt less anxious when teams consisted of more females than males [41]. Furthermore, females perceived their psychological safety to be lower with males than males did with females. This conveys a heightened sense of discomfort for females when interacting with males. In contrast, males do not perceive the same level of discomfort when interacting with females, remaining unaffected by the presence of females. Possible causes suggest that gender status beliefs, which can promote issues for minoritized genders in engineering that do not impact males [44, 45], may be at play. Importantly, such differences in dichotomous interactions raise concerns for interactions at the team level. Individual interactions could transpire as negative interactions that impact the entire team and harm performance due to perceptions between two individuals. While outside of engineering, meta-analysis showed that females tend to have lower perceptions of psychological safety that impair their ability to contribute as much as their male counterparts in teams [46]. Such findings leave implications for engineering design teams, where hesitation in contributing ideas can limit the creativity of design outputs [76-78]. In addition to sharing fewer ideas, lower psychological safety can decrease feeling safe interpersonal risk-taking [73]. Particularly, risk-averse individuals are more against selecting ideas perceived as risky, or “too creative” [79, 80], where risk aversion already tends to be greater in females [81]. As a result, findings at the individual level indicate a need to improve females’ psychological safety in predominantly male teams.

In contrast with findings at the individual level, team level analyses for the second research question did not indicate differences in psychological safety due team gender composition. While prior work showed that greater gender diversity was associated with higher psychological safety [29], our findings aligned with prior work that found no significant relationship [25, 26]. This could be due to the fact that other factors may be at play, such as team characteristics (e.g., personality), team leadership, and problem-solving efficacy [17]. Similarly for the third research question, psychological safety was not found to change significantly by the end of the project as a result of team gender composition. While not analyzed longitudinally, our findings align with prior work in engineering design [24]. Furthermore, while not a direct result of team gender composition, psychological safety was statistically significantly higher at the end of the project in comparison to both the team formation and concept generation stages. From the perspective of design outputs, our findings hint at other factors beyond gender that could impact teams’ productivity and abilities to work together.

4.7 Conclusions, Limitations, and Future Work

The main goal of this paper was to investigate the impact of gender on psychological safety at the individual and team levels. To achieve this goal, we investigated the psychological safety of 19 all-male teams and 19 mixed-gender teams over five distinct time points. The main findings from this study indicated that while a team's gender composition did not have a significant impact on psychological safety, individual dichotomous perceptions of psychological safety were significant. Specifically, females' perceptions of psychological safety with other females were significantly higher than their perceptions with males. Similarly, females had a significantly lower perception of psychological safety with males than males had with females.

While this paper presents results to broaden our view of gender on team interactions in engineering design, this paper does not come without limitations. First, we analyzed gender as two categories for the sake of comparing homogeneous gender composition to heterogeneous gender composition. While dividing the heterogeneous teams into "majority male" and "half male" would have been advantageous for more detailed differences in team gender composition, the given sample size made this impractical. The equal split between homogeneous (N=19) and heterogeneous (N=19) teams was determined to be more statistically sound than breaking up the heterogeneous group into smaller sample sizes for half-male (N=8) and majority male (N=11). Interestingly, prior work pointed to differences between equally split and gender dominant teams, where psychological safety was slightly higher in teams with an equal split [29]. However, these findings were crowdsourced using a scripted team interaction, and not an actual longitudinal team project. Hence, conclusions on team gender composition should be interpreted conservatively until more data is collected.

In addition to difficulties with analyzing teams of a heterogeneous gender composition at a more detailed level, this study cannot be generalized to genders beyond cisgender. Although we gave participants in this study the option to identify as a gender beyond the conventional "male or female" choices that most studies in engineering design use, none of our participants identified as such. To push for a change in the paradigm of how researchers study gender in engineering education [10, 11], we included these options to allow participants of different genders to feel included. Even in a fully cisgender sample, we encourage future work to include more inclusive options when surveying gender demographics.

Future work is also needed that explores these effects in marginalized racial groups. While we collected racial background data, we were not able to analyze it as a variable of interest it due to the extremely low sample size of minoritized races in STEM and at the university being studied. As members of a minoritized race tend to experience microaggressions when interacting with majority race members in STEM [48], future work should investigate how team composition from this perspective impacts psychological safety. Furthermore, work should investigate effects on females of a minoritized race as well, as these individuals tend to experience even more difficulties than majority race females [49].

Aside from limitations with generalizing results to specific demographic backgrounds, reasons behind the lower perceptions of psychological safety for females with males remain limited. Regardless, findings present important implications for studying psychological safety in engineering teams. Particularly, as males remain the dominant gender in engineering [37], constructing female-dominant teams for the sake of making females feel more psychologically safe may not be a feasible solution. As first-year females may lack the confidence needed to provide contributions early on [38], our findings contribute to the knowledge on gender-based issues in engineering design teams in education. Such findings show that problems still exist, and more work is needed to create psychologically safe environments for all individuals. Furthermore, while not the focus of this paper, the participants in this study were under an intervention condition that focused on role assignments [50]. While this intervention could have had impacts on communication patterns similar to anti-bias training, we would anticipate there to be little impact on psychological safety in combination with team gender composition. Thus, we suggest future work to focus on intervention methods that focus on increasing nonmale members' intentions to participate in all design sessions. Finally, while this paper did not focus on increases in team psychological safety at each of the time points alone, the differences between the team formation and ideation sessions with the end of the project point to directions for future work. As psychological safety can impact these design sessions [15, 22], investigating performance outputs from a gender lens could yield interesting implications for how these variables are related.

4.8 References

[1] Cole, C., Jablokow, K., Mohammed, S., and Miller, S., "The Impact of Gender on Individual Perceptions and Team Psychological Safety in Engineering Design Teams," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

[2] Peng, A., Menold, J., and Miller, S. R., "Does It Translate? A Case Study of Conceptual Design Outcomes With U.S. and Moroccan Students," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

[3] Stolk, J. D., Gross, M. D., and Zastavker, Y. V., 2021, "Motivation, pedagogy, and gender: examining the multifaceted and dynamic situational responses of women and men in college STEM courses," International Journal of STEM Education, 8(1), pp. 1-19.

[4] Andrews, M. E., Patrick, A. D., and Borrego, M., 2021, "Engineering students' attitudinal beliefs by gender and student division: a methodological comparison of changes over time," International Journal of STEM Education, 8(1), pp. 1-14.

[5] Marra, R. M., Rodgers, K. A., Shen, D., and Bogue, B., 2009, "Women Engineering Students and Self-Efficacy: A Multi-Year, Multi-Institution Study of Women Engineering Student Self-Efficacy," Journal of Engineering Education, 98(1), pp. 27-38.

[6] Matusovich, H. M., Streveler, R. A., and Miller, R. L., 2010, "Why Do Students Choose Engineering? A Qualitative, Longitudinal Investigation of Students' Motivational Values," Journal of Engineering Education, 99(4), pp. 289-303.

[7] Ayre, M., Mills, J., and Gill, J., 2013, "'Yes, I do belong': the women who stay in engineering," Engineering Studies, 5(3), pp. 216-232.

[8] Maurer, J. A., Choi, D., and Hur, H., 2021, "Building a Diverse Engineering and Construction Industry: Public and Private Sector Retention of Women in the Civil Engineering Workforce," Journal of Management in Engineering, 37(4), pp. 1-11.

[9] Roberts, P., and Ayre, M., 2002, "Did she jump or was she pushed? A study of women's retention in the engineering workforce," International Journal of Engineering Education, 18(4), pp. 415-421.

[10] Haverkamp, A. E., 2021, "Transgender and Gender Nonconforming Undergraduate Engineering Students: Perspectives, Resiliency, and Suggestions for Improving Engineering Education," Doctor of Philosophy, Oregon State University.

[11] Haverkamp, A., Bothwell, M., Montfort, D., and Driskill, Q.-L., 2021, "Calling for a Paradigm Shift in the Study of Gender in Engineering Education," Studies in Engineering Education, 1(2), pp. 55-70.
[12] Weidler-Lewis, J., 2020, "Transformation and Stasis: An Exploration of LGBTQA Students Prefiguring the Social Practices of Engineering for Greater Inclusivity," Engineering Studies, 12(2), pp. 127-149.
[13] Strayhorn, T. L., Long, L. L., Williams, M. S., Dorimé-Williams, M. L., and Tillman-Kelly, D. L., "Measuring the Educational Benefits of Diversity in Engineering Education: A Multi-Institutional Survey Analysis of Women and Underrepresented Minorities," Proc. 2014 ASEE Annual Conference & Exposition, pp. 1-15.
[14] Miller, S., Marhefka, J., Heininger, K., Jablokow, K., Mohammed, S., and Ritter, S., "The Trajectory of Psychological Safety in Engineering Teams: A Longitudinal Exploration in Engineering Design Education," Proc. ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[15] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., "How Engineering Design Students' Psychological Safety Impacts Team Concept Generation and Screening Practices," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[16] Edmondson, A., 1999, "Psychological safety and learning behavior in work teams," Administrative science quarterly, 44(2), pp. 350-383.
[17] Edmondson, A. C., and Lei, Z., 2014, "Psychological Safety: The History, Renaissance, and Future of an Interpersonal Construct," Annual Review of Organizational Psychology and Organizational Behavior, 1(1), pp. 23-43.
[18] Mohammed, S., Ferzandi, L., and Hamilton, K., 2010, "Metaphor no more: A 15-Year review of the team mental model construct," Journal of Management, 36(4), pp. 876-910.
[19] Kozlowski, S. W. J., Chao, G. T., Grand, J. A., Braun, M. T., and Kuljanin, G., 2013, "Advancing Multilevel Research Design:Capturing the Dynamics of Emergence," Organizational Research Methods, 16(4), pp. 581-615.
[20] Kim, J. E., 2021, "Paradoxical Leadership and Proactive Work Behavior: The Role of Psychological Safety in the Hotel Industry," The Journal of Asian Finance, Economics and Business, 8(5), pp. 167-178.
[21] Akan, O. H., Jack, E. P., and Mehta, A., 2020, "Concrescent conversation environment, psychological safety, and team effectiveness," Team Performance Management: An International Journal, 26(1/2), pp. 29-51.
[22] Cole, C., O'Connell, A., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2022, "What Factors Impact Psychological Safety in Engineering Student Teams? A Mixed-Method Longitudinal Investigation," Journal of Mechanical Design, In Review.
[23] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2022, "Does Psychological Safety Impact Team Productivity and Effectiveness During Concept Development? An Exploration in Engineering Design Education," Journal of Mechanical Design, In Review.

[24] Beigpourian, B., Ferguson, D. M., and Ohland, M. W., "The influence of percentage of female or international students on the psychological safety of team," Proc. FYEE Conference.
[25] Leung, K., Deng, H., Wang, J., and Zhou, F., 2015, "Beyond Risk-Taking:Effects of Psychological Safety on Cooperative Goal Interdependence and Prosocial Behavior," Group & Organization Management, 40(1), pp. 88-115.
[26] Carmeli, A., and Gittell, J. H., 2009, "High-quality relationships, psychological safety, and learning from failures in work organizations," Journal of Organizational Behavior, 30(6), pp. 709-729.
[27] Roussin, C. J., Larraz, E., Jamieson, K., and Maestre, J. M., 2018, "Psychological Safety, Self-Efficacy, and Speaking Up in Interprofessional Health Care Simulation," Clinical Simulation in Nursing, 17, pp. 38-46.
[28] Chen, C., Liao, J., and Wen, P., 2014, "Why does formal mentoring matter? The mediating role of psychological safety and the moderating role of power distance orientation in the Chinese context," The International Journal of Human Resource Management, 25(8), pp. 1112-1130.
[29] Lee, H. W., Choi, J. N., and Kim, S., 2018, "Does gender diversity help teams constructively manage status conflict? An evolutionary perspective of status conflict, team psychological safety, and team creativity," Organizational Behavior and Human Decision Processes, 144, pp. 187-199.
[30] Tang, S., Nadkarni, S., Wei, L.-Q., and Zhang, S. X., 2020, "Balancing the Yin and Yang: TMT Gender Diversity, Psychological Safety, and Firm Ambidextrous Strategic Orientation in Chinese High-Tech SMEs," Academy of Management Journal.
[31] Porath, C. L., Overbeck, J. R., and Pearson, C. M., 2008, "Picking Up the Gauntlet: How Individuals Respond to Status Challenges," Journal of Applied Social Psychology, 38(7), pp. 1945-1980.
[32] Anderson, C., John, O. P., Keltner, D., and Kring, A. M., 2001, "Who attains social status? Effects of personality and physical attractiveness in social groups," Journal of Personality and Social Psychology, 81(1), pp. 116-132.
[33] Hirschfeld, R. R., Jordan, M. H., Feild, H. S., Giles, W. F., and Armenakis, A. A., 2005, "Teams' Female Representation And Perceived Potency As Inputs To Team Outcomes In A Predominantly Male Field Setting," Personnel Psychology, 58(4), pp. 893-924.
[34] Frazier, M. L., Fainshmidt, S., Klinger, R. L., Pezeshkan, A., and Vracheva, V., 2017, "Psychological Safety: A Meta-Analytic Review and Extension," Personnel Psychology, 70(1), pp. 113-165.
[35] Bear, J. B., and Woolley, A. W., 2011, "The role of gender in team collaboration and performance," Interdisciplinary Science Reviews, 36(2), pp. 146-153.
[36] Campbell, L. G., Mehtani, S., Dozier, M. E., and Rinehart, J., 2013, "Gender-Heterogeneous Working Groups Produce Higher Quality Science," PLOS ONE, 8(10), pp. 1-6.
[37] Wang, M.-T., and Degol, J. L., 2017, "Gender Gap in Science, Technology, Engineering, and Mathematics (STEM): Current Knowledge, Implications for Practice, Policy, and Future Directions," Educational Psychology Review, 29(1), pp. 119-140.

[38] Laeser, M., Moskal, B. M., Knecht, R., and Lasich, D., 2003, "Engineering Design: Examining the Impact of Gender and the Team's Gender Composition," Journal of Engineering Education, 92(1), pp. 49-56.
[39] Bani-Hani, E., Al Shalabi, A., Alkhatib, F., Eliaghi, A., and Sedaghat, A., 2018, "Factors affecting the team formation and work in project based learning (PBL) for multidisciplinary engineering subjects," Journal of Problem Based Learning in Higher Education, 6(2), pp. 136-143.
[40] Hatmaker, D. M., 2013, "Engineering Identity: Gender and Professional Identity Negotiation among Women Engineers," Gender, Work & Organization, 20(4), pp. 382-396.
[41] Dasgupta, N., Scircle, M. M., and Hunsinger, M., 2015, "Female peers in small work groups enhance women's motivation, verbal participation, and career aspirations in engineering," Proceedings of the National Academy of Sciences, 112(16), pp. 4988-4993.
[42] Lorelle, A. M., and Denise, S., 2013, "The Influence of Gender Stereotypes on Role Adoption in Student Teams," 2013 ASEE Annual Conference & Exposition, ASEE Conferences, Atlanta, Georgia.
[43] Itani, M., and Srour, I., 2016, "Engineering Students' Perceptions of Soft Skills, Industry Expectations, and Career Aspirations," Journal of Professional Issues in Engineering Education and Practice, 142(1), pp. 1-12.
[44] Joshi, A., 2014, "By Whom and When Is Women's Expertise Recognized? The Interactive Effects of Gender and Education in Science and Engineering Teams," Administrative Science Quarterly, 59(2), pp. 202-239.
[45] Hirshfield, L., and Koretsky, M. D., 2018, "Gender and Participation in an Engineering Problem-Based Learning Environment," Interdisciplinary Journal of Problem-Based Learning, 12(1), pp. 1-18.
[46] O'Donovan, R., and McAuliffe, E., 2020, "A systematic review of factors that enable psychological safety in healthcare teams," International Journal for Quality in Health Care, 32(4), pp. 240-250.
[47] Foor, C. E., Walden, S. E., and Trytten, D. A., 2007, "“I Wish that I Belonged More in this Whole Engineering Group:” Achieving Individual Diversity," Journal of Engineering Education, 96(2), pp. 103-115.
[48] Lee, M. J., Collins, J. D., Harwood, S. A., Mendenhall, R., and Huntt, M. B., 2020, "“If you aren't White, Asian or Indian, you aren't an engineer”: racial microaggressions in STEM education," International Journal of STEM Education, 7(1), pp. 1-16.
[49] Camacho, M. M., and Lord, S. M., ""Microaggressions" in engineering education: Climate for Asian, Latina and White women," Proc. 2011 Frontiers in Education Conference (FIE), pp. 1-6.
[50] Scarpinella, S., Cole, C., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., "Can We Get an Intervention, Please? The Utility of Teaming Interventions on Engineering Design Student Psychological Safety," Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[51] Drum, A., Cole, C., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., "Let's Role Play! The Impact of Video Frequency and Role Play on the Utility of a Psychological

Safety Team Intervention," Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[52] Rosser, S. V., 1998, "Group work in science, engineering, and mathematics: Consequences of ignoring gender and race," College Teaching, 46(3), pp. 82-88.
[53] Tuong, W., Larsen, E. R., and Armstrong, A. W., 2014, "Videos to influence: a systematic review of effectiveness of video-based education in modifying health behaviors," Journal of Behavioral Medicine, 37(2), pp. 218-233.
[54] Yousef, A. M. F., Amine, M. C., and Schroeder, U., 2014, "The State of Video-Based Learning: A Review and Future Perspectives," International Journal on Advances in Life Sciences, 6(3/4), pp. 122-135.
[55] Dym, C. L., and Little, P., 2014, Engineering design: A project-based introduction, John Wiley and sons.
[56] Pugh, S., 1991, Total Design: Integrated Methods for Successful Product Engineering, Addison-Wesley.
[57] Berge, Z. L., 1998, "Differences in teamwork between post-secondary classrooms and the workplace," Education + Training, 40(5), pp. 194-201.
[58] Blumenfeld, P. C., Marx, R. W., Soloway, E., and Krajcik, J., 1996, "Learning with peers: From small group cooperation to collaborative communities," Educational Researcher, 25(8), pp. 37-39.
[59] Fredrick, T. A., 2008, "Facilitating better teamwork: Analyzing the challenges and strategies of classroom-based collaboration," Business Communication Quarterly, 71(4), pp. 439-455.
[60] Kinlaw, D. C., 1991, Developing superior work teams: Building quality and the competitive edge, Lexington Books.
[61] Ericksen, J., and Dyer, L., 2004, "Right from the Start: Exploring the Effects of Early Team Events on Subsequent Project Team Development and Performance," Administrative Science Quarterly, 49(3), pp. 438-471.
[62] Parsons, M. L., Batres, C., and Golightly-Jenkins, C., 2006, "Innovations in Management: Establishing Team Behavioral Norms for a Healthy Workplace," Advanced Emergency Nursing Journal, 28(2), pp. 113-119.
[63] Taggar, S., and Ellis, R., 2007, "The role of leaders in shaping formal team norms," The Leadership Quarterly, 18(2), pp. 105-120.
[64] Kress, G. L., and Schar, M., 2012, "Teamology – The Art and Science of Design Team Formation," Design Thinking Research: Studying Co-Creation in Practice, H. Plattner, C. Meinel, and L. Leifer, eds., Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 189-209.
[65] Mohan, G., and Lee, Y., 2019, "Temporal Dynamics of Collective Global Leadership and Team Psychological Safety in Multinational Teams: An Empirical Investigation," Advances in Global Leadership, Emerald Publishing Limited, pp. 29-47.
[66] Liu, Y., Keller, R. T., and Bartlett, K. R., 2021, "Initiative climate, psychological safety and knowledge sharing as predictors of team creativity: A multilevel study of research and development project teams," Creativity and Innovation Management, 30(3), pp. 498-510.

[67] Zhang, Y., Fang, Y., Wei, K.-K., and Chen, H., 2010, "Exploring the role of psychological safety in promoting the intention to continue sharing knowledge in virtual communities," International Journal of Information Management, 30(5), pp. 425-436.
[68] Charyton, C., and Merrill, J. A., 2009, "Assessing general creativity and creative engineering design in first year engineering students," Journal of Engineering Education, 98(2), pp. 145-156.
[69] Cropley, D. H., 2016, "Creativity in Engineering," Multidisciplinary Contributions to the Science of Creative Thinking, G. E. Corazza, and S. Agnoli, eds., Springer Singapore, Singapore, pp. 155-173.
[70] Cropley, D. H., and Cropley, A. J., 2000, "Fostering creativity in engineering undergraduates," High Ability Studies, 11(2), pp. 207-219.
[71] Paulus, P., 2000, "Groups, teams, and creativity: The creative potential of idea-generating groups," Applied Psychology, 49(2), pp. 237-262.
[72] Thompson, G., and Lordan, M., 1999, "A review of creativity principles applied to engineering design," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 213(1), pp. 17-31.
[73] Kessel, M., Kratzer, J., and Schultz, C., 2012, "Psychological Safety, Knowledge Sharing, and Creative Performance in Healthcare Teams," Creativity and Innovation Management, 21(2), pp. 147-157.
[74] Edmondson, A. C., 2003, "Speaking Up in the Operating Room: How Team Leaders Promote Learning in Interdisciplinary Action Teams," Journal of Management Studies, 40(6), pp. 1419-1452.
[75] Edmondson, A. C., 2002, Managing the risk of learning: Psychological safety in work teams, Cambridge, MA: Division of Research, Harvard Business School.
[76] Burningham, C., and West, M. A., 1995, "Individual, Climate, and Group Interaction Processes as Predictors of Work Team Innovation," Small Group Research, 26(1), pp. 106-117.
[77] Connelly, C. E., and Kevin Kelloway, E., 2003, "Predictors of employees’ perceptions of knowledge sharing cultures," Leadership & Organization Development Journal, 24(5), pp. 294-301.
[78] Ehrlenspiel, K., and Dylla, N., 1993, "Experimental Investigation of Designers' Thinking Methods and Design Procedures," Journal of Engineering Design, 4(3), pp. 201-212.
[79] Toh, C. A., and Miller, S. R., 2016, "Choosing creativity: the role of individual risk and ambiguity aversion on creative concept selection in engineering design," Research in Engineering Design, 27(3), pp. 195-219.
[80] Toh, C. A., and Miller, S. R., 2016, "Creativity in design teams: the influence of personality traits and risk attitudes on creative concept selection," Research in Engineering Design, 27(1), pp. 73-89.
[81] Borghans, L., Heckman, J. J., Golsteyn, B. H., and Meijers, H., 2009, "Gender differences in risk aversion and ambiguity aversion," Journal of the European Economic Association, 7(2-3), pp. 649-658.
[82] Kolodner, J. L., and Wills, L. M., 1996, "Powers of observation in creative design," Design Studies, 17(4), pp. 385-416.

[83] Brereton, M., and McGarry, B., 2000, "An observational study of how objects support engineering design thinking and communication: Implications for the design of tangible media," SIGCHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, The Hague, The Netherlands, pp. 217–224.
[84] Buchenau, M., and Suri, J. F., 2000, "Experience prototyping," 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, Association for Computing Machinery, New York City, New York, USA, pp. 424–433.
[85] Yang, M. C., 2005, "A study of prototypes, design activity, and design outcome," Design Studies, 26(6), pp. 649-669.
[86] McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., and Vera, A., 2006, "Breaking the fidelity barrier: An examination of our current characterization of prototypes and an example of a mixed-fidelity success," SIGCHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, Montréal, Québec, Canada, pp. 1233–1242.
[87] Starkey, E. M., Menold, J., and Miller, S. R., 2019, "When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk," Journal of Mechanical Design, 141(3), pp. 1-9.
[88] Wolfe, J., Powell, E. A., Schlisserman, S., and Kirshon, A., 2016, "Teamwork in Engineering Undergraduate Classes: What Problems Do Students Experience?," 2016 ASEE Annual Conference & Exposition, ASEE Conferences, New Orleans, Louisiana.
[89] Zimmerman, D. H., and West, C., 1996, "Sex roles, interruptions and silences in conversation," Towards a Critical Sociolinguistics, R. Singh, ed., John Benjamins, pp. 211-236.
[90] LeBreton, J. M., and Senter, J. L., 2008, "Answers to 20 Questions About Interrater Reliability and Interrater Agreement," Organizational Research Methods, 11(4), pp. 815-852.
[91] Fisher, R. A., 1925, "Theory of Statistical Estimation," Mathematical Proceedings of the Cambridge Philosophical Society, 22(5), pp. 700-725.
[92] Tavakol, M., and Dennick, R., 2011, "Making sense of Cronbach's alpha," Int J Med Educ, 2, pp. 53-55.
[93] Ito, P. K., 1980, "7 Robustness of ANOVA and MANOVA test procedures," Handbook of Statistics, Elsevier, pp. 199-236.
[94] Magezi, D. A., 2015, "Linear mixed-effects models for within-participant psychology experiments: an introductory tutorial and free, graphical user interface (LMMgui)," Frontiers in Psychology, 6(2), pp. 1-6.
[95] Li, T., Castro, L. M. C., Douglas, K., and Brinton, C. G., "Relationship between learning engagement metrics and learning outcomes in online engineering course," Proc. 2021 IEEE Frontiers in Education Conference (FIE), pp. 1-5.

CHAPTER 5

CONCLUSIONS AND CONTRIBUTIONS

Since the reveal of Google's Project Aristotle promoting psychological safety as the leading factor in what makes teams outperform others [5], various entities in education and industry have been looking to use this construct as way to observe and improve team interactions. For engineering design teams in education, working towards this improvement remains a critical goal due to the widespread belief that teams are seen as more effective than individuals alone when solving complex problems. However, when teams spend more time trying to figure out how to work together than actually solving the problem at hand, this can be detrimental to team performance. Specifically, prior work outside of engineering showed that when team members do not feel psychologically safe, they may be apprehensive to take interpersonal risks and not feel valued enough to share their ideas [7, 8]. Such findings allude to a potential impact on design outputs through limiting innovation due to the relationship between risk-taking aversion and selecting creative concepts [15], for example. In general, implications from previous studies in engineering design can be used to hypothesize that psychological safety may have an impact on design outputs in engineering design through claims of psychological safety's positive influence on creativity in work outside of engineering design [29, 104]. However, prior work has not proven that psychological safety may actually be of importance when considering engineering design team performance. Therefore, this dissertation aimed to establish identify the impact of psychological safety in engineering design student teams and the factors underlying its establishment.

To identify some of the inputs and outputs of psychological safety in engineering design teams in education, the current dissertation aimed at exploring these relationships through three studies. Specifically, Paper I (Chapter 2) explored the role of psychological safety its relationship to the fluency and goodness of design ideas generated, and the underlying role of idea ownership. From there, Paper II (Chapter 3) explored how individual cognitive style with individual perceptions of psychological safety could be used to predict the paradigm-relatedness of design outputs generated at concept generation. Furthermore, it investigated how cognitive style diversity and elevation can be applied together in conjunction with team psychological safety to predict the paradigm-relatedness of the selected concepts and the concepts of the functional prototypes. Finally, Paper III (Chapter 4) investigated how individual gender and team gender composition can be used to influence the establishment, building, and maintenance of psychologically safe environments during a multi-week engineering design team project. The knowledge gained from this research can be applied to facilitate our understanding of psychological safety in engineering design teams and how antecedents to psychological safety could be applied to promote better team performance. This dissertation also provides the groundwork for the future development of specialized intervention methods to address team issues and foster psychological safety. Finally, the knowledge gained from these studies can help researchers in engineering education understand how psychological safety may apply to team projects in their courses. The following sections of this chapter synthesize the findings of the three papers in this dissertation and point out future research directions. A summary of the findings is shown in Appendix C.

5.1 Psychological safety shares an inverse relationship with idea fluency during concept generation practices, but not the paradigm-relatedness of individual ideas

The first main contribution of this dissertation is the identification of the relationships between engineering design outputs during the concept generation stage. In Paper I (Chapter 2), results showed an inverse relationship between team psychological safety and idea fluency, or the total number of ideas per team (normalized per the number of team members that contributed in the design session in this study). This meant that as teams' psychological safety scores increased, the normalized number of ideas per team decreased. This finding suggests that both researchers and instructors in engineering design education should pay attention to this form of "comfort," where team members may feel relaxed together, making the team unlikely to push themselves to explore other solutions that may push the boundaries of the solution space. In contrast, findings from Paper II (Chapter 3) did not significantly predict the likelihood of the paradigm-relatedness of individually-generated concepts from concept generation using psychological safety and cognitive style, or one's preferred problem-solving style [40]. This suggests that feeling psychologically safe within a team does not necessarily lead to individuals producing concepts that align with their preferences for problem-solving (i.e., generating more incremental solutions than radical solutions, or vice versa). On the other hand, controlling for design task was a significant predictor for the types of solutions that student designers come up with, aligning with prior work [144].

5.2 Psychological safety shares a positive relationship with concept screening practices, but not selection practices

In addition to the relationship between concept generation design outputs and psychological safety, the current work identified a relationship between the perceived goodness of the individual concepts generated during concept generation. Specifically, in Paper I (Chapter 2), higher team psychological safety shared a positive relationship with the average perceived goodness of ideas within the teams. This meant that the more psychologically safe teams felt, the more the average idea goodness of all members would increase. Such findings point to a potential relationship between psychological safety and trusting others' ideas through screening the solutions as "consider" to give them a chance. Because prior work has already established a connection between trust and psychological safety [8], further investigation on the social interactions that may influence screening practices, such as trust, is needed.

When analyzing the relationship between psychological safety and ownership bias, Paper I (Chapter 2) incidences of ownership bias could not be predicted using psychological safety. Such results convey that if ownership bias had occurred, there could be other underlying factors, such as gender [36], that would have been more influential than psychological safety. From there, Paper II (Chapter 3) investigated how team psychological safety and cognitive style diversity/elevation can be used to predict the percentage of the ideas in each paradigm-relatedness category that a team selects for low-fidelity prototyping. While findings showed that both psychological safety and team cognitive style metrics were not statistically significant, the controlling for the availability of ideas in each paradigm-relatedness category was statistically significant. Aligning with prior work that identified that the availability of certain ideas influences the kinds of ideas that will survive the selection process [59], these findings show that concept generation practices are important for the kinds ideas that survive screening and selection processes. Taken as a whole, the findings from Paper I (Chapter 2) and Paper II (Chapter 3) established directions for further empirical investigations that could assess to what extent psychological safety may be impactful on other interactions and performance outputs during these design activities.

5.3 Only cognitive style diversity was related to the paradigm-relatedness of the concepts behind the functional prototypes

Elaborating on the findings presented in the previous two sections of this chapter, psychological safety was not found to be statistically significant in predicting the paradigm-relatedness of specific design outputs at the concept generation, concept selection, and prototyping stages of the engineering design process. Specifically, results from Paper II (Chapter 4) showed that feeling psychologically safe had no significant bearing on whether individuals or teams generated or selected concepts that aligned with their cognitive styles. Furthermore, incidences of cognitive style diversity were significant only when teams collectively selected the design for their functional prototype. This meant that KAI diversity (the metric used to represent cognitive style diversity) was a significant predictor for teams selecting more paradigm-challenging and paradigm-breaking functional prototype concepts over paradigm-consistent concepts. Such results imply that on the surface, cognitive style does not become an important predictor of design outputs until the prototyping stage. However, results could be confounded simply due to the psychological safety scale's inability to capture interactions such as coping behavior, which can contribute to a misalignment between cognitive style and the kinds of design outputs produced by teams and individuals [39, 87]. Overall, the results from Paper II (Chapter 4) established future directions for investigating the role of other confounding factors that could be impacting the paradigm-relatedness of design outputs.

5.4 Females felt less psychologically safe with males, however effects were not apparent at the team level

After establishing some of the potential relationships between psychological safety and various outputs in the engineering design process, Paper III (Chapter 4) established a baseline for antecedents to psychological safety. Specifically, main findings showed that dichotomous individual perceptions of psychological safety were statistically significant, where females felt less psychologically safe with males than males did with females, and females felt less psychologically safe with males than they did with other females. These findings indicated that females experience a heightened sense of discomfort when interacting with males. On the other hand, males do not perceive the same level of discomfort when interacting with females, remaining unaffected by the presence of females. These outcomes could be due to gender status beliefs, which can promote issues for underrepresented genders in engineering that do not affect males [145, 146]. In all, these results show that there is still more work to do to help females feel more psychologically safe in engineering.

When females feel less psychologically safe under the influence of gender, such differences in the dichotomous interactions could be problematic at the team level. For example, if team members do not feel psychologically safe to contribute ideas, this lack of sharing could have a negative impact on the creativity of design outputs [30, 125, 147]. In addition to sharing fewer ideas, lower psychological safety can decrease feeling safe for interpersonal risk-taking [29], where risk-averse individuals are more against selecting ideas perceived as risky [15, 74]. This aversion can be even more detrimental to design outputs, as prior work showed that risk aversion already tends to be greater in females than males [148]. These results could be critical to design outputs, such as those examined in Paper I (Chapter 2) and Paper II (Chapter 3). For example, when females feel less psychologically safe than males, lower psychological safety could result in lower perceptions of idea goodness, particularly from females. Taken as a whole, these findings at the individual level indicate the need to improve females' psychological safety in predominantly male teams to not only improve the design process, but to make engineering design education more equitable for students of all genders.

Apart from the individual level analysis, team level analyses on team gender composition showed that team gender composition did not significantly impact differences in team psychological safety. Specifically, Paper III (Chapter 4) showed that over a trajectory of five time points in the engineering design process, neither one of the time points had any significant variation in team psychological safety when comparing gender homogeneous (all male) to gender heterogeneous (mixed male and female) teams. Results also showed that when comparing the end of the project to the very beginning of the project, teams did not experience a significant change in psychological safety in either of the two types of team compositions. However, psychological safety was significantly different between some of the time points, where teams had lower psychological safety at both the *team formation* and *concept generation* stages in comparison to the *final deliverables* stage. This conveys other factors besides gender may influence team productivity through psychological safety, and certain interactions that occur during these design stages may elicit interactions that lead to either the waning or building of team psychological safety.

5.5 Key Findings on Psychological Safety in Engineering Education and Expanding its Importance to Industry

To understand the findings of this dissertation as a whole, the three papers presented throughout this document can be summarized as follows. Specifically, the individual-level analysis on gender showed that gender as an input influences individual dichotomous perceptions of psychological safety within teams at the end of the project. This finding implies that the lack of safety that females encounter may be impacting their ability to participate in the design process. Further analyses on gender at the team level present implications for other design outputs as well. For example, while not significantly different due to gender, psychological safety was significantly higher at the final deliverables stage in comparison to both the team formation and concept generation stages. This finding implies that interactions at the team formation stage, which is where team norms are established [51, 53, 54], as well as the concept generation stage, which is where teams seek to develop creative solutions to a given problem [31, 149-152], may be at risk. Because these earlier stages lead up to the final design, instructors should pay attention to team interactions at these stages. Furthermore, psychological safety was shown to share an inverse relationship with the number of ideas that teams produce, but what can be said for the quality of these ideas remains inconclusive.

Even though psychological safety was not shown to significantly predict the likelihood for these concepts being categorized within any of the three categories that determines how incremental or radical an idea is (paradigm-relatedness), it was found that the design task alone was enough to predict this outcome. In fact, psychological safety was not shown to significantly predict any of the outcomes for the paradigm-relatedness of concepts at the generation, selection, and prototyping stages. However, psychological safety did share a positive relationship with idea goodness, or the team members' perceptions of the quality of others' ideas [36], during the screening stage. On the other hand, ownership bias, or the tendency for others to select their own ideas [70], failed to show a significant relationship with psychological safety. These findings imply that when team members are more psychologically safe, this form of safety could tap into feelings of trust that encourage them to consider others' ideas in the next stage of the design process.

While the findings of this dissertation have overarching implications for the engineering design process in education, translating the findings already presented here to an industry environment remain critical for establishing psychological safety's importance outside of education. Particularly, industry initiatives and perspectives tend to less comfortable and effective when discussing topics such gender bias, even when there is an honest attempt to address the issue [153]. This is problematic, as females, a minoritized gender in STEM fields, have reported feeling negatively judged by their gender [114] and are pushed into assuming more secretarial roles [154], for example. One perspective that academics can take is relating constructs such as psychological safety to engineering failures. For example, the Challenger space shuttle disaster of 1986 was more than just an issue with O-rings failing in cold temperatures, but rather managers at Morton Thiokol were coerced by NASA officials into ignoring and dismissing their own engineers' concerns [155]. As a result, engineers lacked the psychological safety to speak up any further [156, 157], ultimately leading to the explosion of the Challenger and death of seven people aboard the shuttle. Such drastic outcomes can be construed as a lack of psychological safety within the group, but without making this connection for those working in industry, bringing up psychological safety may come across as another coined term in organizational psychology. Furthermore, we can encourage industry professionals to consider other potential factors in these situations, such as discrepancies in gender balance or other forms of diversity under a lens of not politically-charged constructs (such as belonging uncertainty [158]). Thus, unless our findings in academia are shared and translated to the industry environments, team leaders and employees in engineering industry may not recognize potentially ongoing problems in their teams. Such deficiencies could lead to failure in employee retention (particularly for females and other minoritized groups in engineering and technology [159, 160]), and worse yet, the loss of human life and billions of dollars [161].

Building onto the discussion of translating the importance of psychological safety to an industry environment, specific findings from this dissertation can also be translated to industry in a meaningful way. For example, if we look at the findings from Paper I (Chapter 2), one of the findings showed that psychological safety shared an inverse relationship with normalized idea fluency. While this finding can get at the "dark side of psychological safety" where team members "slack away in comfort," [81], this finding points to an even deeper and more impactful issue for industry: engaging in unethical activity through prioritizing utilitarianism [80]. Referring back to the Challenger accident, such interactions within management teams could be said to be emulating the same negative behavior. Specifically, business and imposed deadlines took precedence over the safety of others when making the decision to launch the spacecraft [156]. While it may be a stretch, we can think of the management cohort as feeling psychologically safe to prioritize this unethical behavior for the sake of business's interests. This idea alludes to them feeling psychologically safe enough to not explore more options to the issue at hand. Because prior work showed that increases in the idea fluency studied in this dissertation is linked to being able to explore the solution space [35], such a connection can be made to failing to explore other solutions in certain industry cohorts.

While the first finding from Paper I presented some concerns for industry in terms of psychological safety in certain cohorts, the second finding showed that psychological safety shares a positive relationship with teams' average idea goodness scores. This finding gets at increases in psychological safety promoting team members to trust others' ideas enough within the group enough to consider putting them into practice. For example, in the Challenger case, the engineering cohort may have felt psychologically safe enough with one another to trust that the idea of speaking out against the launch was the right thing to do. That being said, Paper II (Chapter 3) failed to show any significant outcomes when investigating psychological safety and the paradigm-relatedness of design outputs. This hints that other factors such as coping behavior [39] may play a role in industry teams, where leadership style can vary and influence creative performance [162]. This is not to say that creative outputs in engineering cannot be affected by psychological safety, especially with the abundance of literature on psychological safety and creativity [29, 106, 117], but rather other factors may be more dominant in predicting how individuals and teams come up with more incremental or radical solutions. However, more work is needed to make such conclusions for industry professionals in engineering. In conclusion, while these findings point to potential implications for industry, it is important to clarify that education and industry are not the same environments and implications for each may vary. However, being that the students studied in this dissertation may be the very people who go into these high-risk engineering careers, these results hold importance for building an understanding of how industry employees' interactions within teams may impact team performance.

5.6 Limitations and Future Directions

While this dissertation presented the role of psychological safety in the design process and established a baseline for investigating antecedents to the psychological safety that can impact design processes, there are several limitations. First, while the results in this dissertation demonstrated an inverse relationship between team psychological safety and normalized idea fluency, the effect size of this relationship was small. Additionally, while this study revealed a positive relationship between psychological safety and the average idea goodness of a team's ideas, the effect size of this relationship was also small. These findings indicate that other factors may contribute to how many ideas individuals can propose. Prior work found that both design task [144] and prior background knowledge [163] can influence design outputs. Such factors could influence how many ideas a student feels that they can generate (idea fluency), or how well they understand the design task to agree with others' ideas (idea goodness). While these findings were surprising at first (particularly the inverse relationship between psychological safety and idea fluency), the small effect sizes indicate that there is more work that can be done when it comes to accounting for other variables in the analyses. When considering a combination of the idea fluency and goodness metrics together (such as a weighted goodness of ideas paired with the number of ideas generated), preliminary analyses showed lack of a significant relationship between idea fluency and the goodness of these ideas. Analyzing idea fluency at greater detail in future work could be beneficial, however, it was not a critical goal of this first paper. Furthermore, using idea goodness to detect ownership bias serves as a proxy [69]. Because the emergence of ownership bias may be too implicit to detect through verbalized interactions [69], using idea authors' ratings serves as a reasonable, however indirect method to detecting ownership bias. This imposes a risk that ownership bias may actually occur in ways not explicitly presented in the empirical results, limiting our interpretation of how psychological safety may influence this bias.

When psychological safety at Time Point 3 was used to represent teams' psychological safety during concept screening, this occurred in the same session as concept selection (analyzed in Paper II). Therefore, there is a chance that some interactions may have occurred between them, impacting psychological safety measures at the end of the class. However, effects are expected to be minimal due to the short amount of time (less than an hour) that had elapsed between the events. Although psychological safety could have been measured twice via the survey in the same class period, the time between the events would be too short, where respondents may have memorized the survey [164].

In contrast with Paper I (Chapter 2), findings from the investigation of psychological safety and cognitive style on the paradigm-relatedness of design outputs at in Paper II (Chapter 3) presented limitations as well. For example, an individual's tacit knowledge about a particular design task can influence the kinds of concepts that they propose [163], as well as how an individual engages in coping behavior [39]. Furthermore, individual perceptions of psychological safety were included to capture how safe individuals felt to take risks via sharing unique ideas. However, statistical insignificance shows that psychological safety does not necessarily capture the coping behavior that may drive more adaptive individuals to produce innovative outputs, and vice versa [39]. Thus, this study establishes the need to include explicit measures of coping behavior to control for any effects it may have on the paradigm-relatedness of individually generated concepts.

Along with individual-level analyses, the team-level analyses in Paper II (Chapter 3) are subject to limitations as well. Particularly, coping behavior may add a layer of complexity to teams' decision processes. While aggregation models typically assume that all team members will be represented equally [97], this is not always the case. Some individuals may have more influence through controlling the team discussion, allowing them to push their preferences upon others and ultimately get what they want [102]. As a result, team members who are apprehensive to challenge the decision give in to the dominating member's wants. Such dialogues could show incidences of ownership bias as well, which was investigated in Paper I (Chapter 2), but was not detected. Furthermore, prior work has found that when gender faultlines are activated through either a design task perceived as more feminine or masculine, design outputs such as idea fluency and overall creativity may be lower [112]. While perceptions of design prompts from the perspective of feminine versus masculine were not investigated in this dissertation, future work may benefit from exploring these variables along with psychological safety and design outputs. In all, the lack of significance from psychological safety in all analyses in Paper II was also a bit surprising. However, this lack of significance could be due to needing to account for other team constructs in future analyses.

In addition to the limitations that found limited effects of psychological safety in the engineering design process, the investigation on gender as an antecedent to psychological safety presented limitations as well. Specifically, results on team gender composition presented in Paper III (Chapter 4) are limited by analyzing gender using just two categories. Gender homogeneous was represented as all males, as females and other genders tend to be minoritized in STEM fields and consequently, the number of members in the minoritized groups tends to be far less than males. This sample size issue was propagated to teams in the gender heterogeneous category. Specifically, 8 teams in the study were half male, whereas the remaining 11 teams were majority male; all of which were less than the number of all male teams: 19 teams. Although keeping the gender breakdown as two different groups allowed the sample sizes to be equal, there could be differences between the majority male and half male teams. Specifically, prior work outside engineering design education pointed to differences in psychological safety in teams depending on this breakdown, where equal gender teams tended to have higher psychological safety than majority gender [50]. Therefore, future work in engineering design education should focus on collecting more data with greater variations in breakdowns of team gender composition to understand how more specific configurations of genders on a team could impact team psychological safety over time.

To further understand the impacts of team gender composition on teams with minoritized individuals, future work would also benefit from oversampling specific team configurations in a controlled study. Specifically, organizing teams with equal sample sizes of both different gender and racial background compositions could help to understand to what extent these team breakdowns may have an impact on psychological safety. Because prior work has found that not only do female students report perceived biases because of their gender [114], but other work has shown minoritized racial background members to report similar issues [128, 129], controlling for this in future studies could be informative in knowing what could cause negative interactions to arise and how to address them. This form of oversampling could be applied to studies such as those in Papers I and II to investigate how team configurations may influence engineering design outputs, as teams with a more dominant gender or race may vary in terms of their design outputs.

Adding to developing a deeper understanding of team gender composition, the individual level analyses would benefit from future work that focuses on why female perceptions of psychological safety are lower than males' perceptions. While Paper III provided several speculations of why females' perceptions were lower than males' perceptions, constructs such as belonging uncertainty, or the concern about the quality of one's social ties to the group [158], raise questions about how females felt connected to their teams. Future work would benefit from exploring the relationship between gender-based perceptions of psychological safety and the willingness to work on a given team again.

While expanding on individual and team levels of gender composition should be a direction for future work, expanding the scope to include racial background as a predictor is a critical goal as well. Specifically, prior work showed that members of marginalized racial backgrounds may experience microaggressions when interacting with majority race members in STEM [128]. Even worse, females from minoritized racial groups have reported even more difficulties than majority race females in the STEM environment [129]. Therefore, future work should collect more data from these minoritized groups to understand how both racial background and gender impact psychological safety.

As a whole, this dissertation showed that psychological safety has differential effects when observed under different variables at different stages of the engineering design process. Specifically for Paper III, results showed that gender was a significant predictor of psychological safety at the individual level, but not at the team level. On the other hand, results from Paper II showed that psychological safety did not have any significant influence any of the outcomes. While coping behavior may play a role in such outcomes, this is only speculation. Therefore, expanding upon the findings of this dissertation as a whole to include both gender as well as account for coping behavior, may help to understand to what extent psychological safety plays a role in predicting various kinds of design outputs. Design outputs should also extend beyond what was covered in this dissertation to give a more thorough view of how psychological safety and other inputs are related to measures of individual and team performance. Furthermore, because Paper III showed significant effects at the individual level with respect to gender and psychological safety, future work would benefit from more controlled studies at the individual and team levels when comparing groups. Particularly, such controls would be useful for when looking at the combination of gender breakdowns and how coping behavior may unfold within specific interactions. Adding to the previously mentioned point about controlling for gender and racial background, carrying out these controls could help to develop a fuller picture of how psychological safety plays a role at both the individual and team levels (while also promoting an equal sample size of dichotomous ratings between females and females (or other nonmales) in comparison to dichotomous ratings that stem from the perception of already abundant males in engineering education). Finally, future work would benefit from exploring the differences between groups exposed to interventions focused on improving psychological safety in teams and non-intervention groups. Because Paper III had a gender balance created on purpose and the teams were also exposed to an intervention on psychological safety, this could have acted as an "anti-bias" training in some ways. Therefore, it is possible that the non-intervention results may vary, but more work would be needed to make an assertion.

APPENDIX A – DEMOGRAPHICS SURVEY

Demographic Information

Please write legibly.

Your name (first and last): ____________________________

Age: ______________

Gender: ______________

☐ Male ☐ Female ☐ Trans male/trans man ☐ Trans female/trans woman

☐ Genderqueer/gender non-conforming ☐ Different identity (please state above)

☐ Prefer not to respond

How would you describe yourself? (Choose one or more from the following racial groups):

☐ American Indian/Alaska Native ☐ Asian ☐ Native Hawaiian/Other Pacific Islander

☐ Black/African American ☐ White ☐ More than One Race

☐ Prefer not to answer

Intended Major: _________

ie: Mechanical Engineering, Industrial Engineering, Chemical Engineering, etc.

Semester Standing: _______

ie: If this is your first semester at Penn State, write down "1". If it is your second, write down "2", and so on.

APPENDIX B – PSYCHOLOGICAL SAFETY SURVEY

Please select a response to each of the items below on how you feel it represents your feelings:

	Very Inaccurate (1)	(2)	(3)	(4)	(5)	(6)	Very Accurate (7)
If you make a mistake on this team, it is often held against you.	○	○	○	○	○	○	○
Members of this team are able to bring up problems and tough issues.	○	○	○	○	○	○	○
People on this team sometimes reject others for being different.	○	○	○	○	○	○	○
It is safe to take a risk on this team.	○	○	○	○	○	○	○
It is difficult to ask other members of this team for help.	○	○	○	○	○	○	○
No one on this team would deliberately act in a way that would undermine my efforts.	○	○	○	○	○	○	○
Working with the members of this team, my unique skills and talents are valued and utilized.	○	○	○	○	○	○	○

APPENDIX C – SUMMARY OF MAIN FINDINGS OF THIS DISSERTATION

	Paper I			Paper II	Paper III	
	Outputs			Outputs	Inputs	
	Idea Fluency	**Idea Goodness**	**Ownership Bias**	**Paradigm-Relatedness**	**Individual Dichotomous Perceptions of Gender**	**Team Gender Composition**
Team Formation						Team gender composition did not significantly predict differences in psychological safety over the five time points in the engineering design process, nor was there a significant difference in psychological safety by the end of the project when controlling for psychological safety at the beginning. In general, psychological safety was significantly higher at the final deliverables stage in comparison to the team formation and concept generation stages.
Concept Generation	There was a significant inverse relationship with team psychological safety and idea fluency.			Individual cognitive style and perceptions of psychological safety did not significantly predict the likelihood of the paradigm-relatedness of concepts; only design task was significant.		
Concept Screening & Selection		There was a significant relationship between team psychological safety and perceptions of idea goodness.	There was no significant relationship between psychological safety and ownership bias.	Neither cognitive style diversity nor psychological safety were significant predictors for the percent of concepts selected in each category. Controlling for the percentage of concepts in each category was significant.		
Prototyping				Only cognitive style diversity was significant for predicting the paradigm-relatedness of functional prototype concepts, but not psychological safety.		
Final Deliverables					At the end of the project, females felt less psychologically safe with males than they do other females. Females also felt less psychologically safe with males than males felt with females.	

BIBLIOGRAPHY

[1] Williamson, J. M., Lounsbury, J. W., and Han, L. D., 2013, "Key personality traits of engineers for innovation and technology development," Journal of Engineering and Technology Management, 30(2), pp. 157-168.
[2] Cohen, S. G., and Bailey, D. E., 1997, "What makes teams work: Group effectiveness research from the shop floor to the executive suite," Journal of management, 23(3), pp. 239-290.
[3] Hubka, V., and Ernst Eder, W., 1987, "A scientific approach to engineering design," Design Studies, 8(3), pp. 123-137.
[4] Mathieu, J., Maynard, M. T., Rapp, T., and Gilson, L., 2008, "Team effectiveness 1997-2007: A review of recent advancements and a glimpse into the future," Journal of management, 34(3), pp. 410-476.
[5] Rozovsky, J., 2015, "The five keys to a successful Google team," Retrieved from https://rework.withgoogle.com.
[6] Duhigg, C., 2016, "What Google learned from its quest to build the perfect team," The New York Times Magazine.
[7] Edmondson, A., 1999, "Psychological safety and learning behavior in work teams," Administrative science quarterly, 44(2), pp. 350-383.
[8] Edmondson, A. C., and Lei, Z., 2014, "Psychological Safety: The History, Renaissance, and Future of an Interpersonal Construct," Annual Review of Organizational Psychology and Organizational Behavior, 1(1), pp. 23-43.
[9] Frazier, M. L., Fainshmidt, S., Klinger, R. L., Pezeshkan, A., and Vracheva, V., 2017, "Psychological Safety: A Meta-Analytic Review and Extension," Personnel Psychology, 70(1), pp. 113-165.
[10] Miller, S., Marhefka, J., Heininger, K., Jablokow, K., Mohammed, S., and Ritter, S., "The Trajectory of Psychological Safety in Engineering Teams: A Longitudinal Exploration in Engineering Design Education," Proc. ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[11] Dylla, N., 1991, "Thinking methods and procedures in mechanical design," PhD, Technical University of Munich, Munich, Germany.
[12] Dym, C. L., and Little, P., 2014, Engineering design: A project-based introduction, John Wiley and sons.
[13] Plan, E. T., and Khandani, S., 2005, "Engineering design process."
[14] Pugh, S., 1991, Total Design: Integrated Methods for Successful Product Engineering, Addison-Wesley.
[15] Toh, C. A., and Miller, S. R., 2016, "Choosing creativity: the role of individual risk and ambiguity aversion on creative concept selection in engineering design," Research in Engineering Design, 27(3), pp. 195-219.
[16] Amabile, T. M., 1988, "A model of creativity and innovation in organizations," Research in organizational behavior, 10(1), pp. 123-167.

[17] Starkey, E. M., Menold, J., and Miller, S. R., 2019, "When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk," Journal of Mechanical Design, 141(3).
[18] Jonassen, D. H., and Kim, B., 2010, "Arguing to learn and learning to argue: Design justifications and guidelines," Educational Technology Research and Development, 58(4), pp. 439-457.
[19] Jonassen, D. H., and Cho, Y. H., 2011, "Fostering Argumentation While Solving Engineering Ethics Problems," Journal of Engineering Education, 100(4), pp. 680-702.
[20] Edmondson, A. C., 2003, "Speaking Up in the Operating Room: How Team Leaders Promote Learning in Interdisciplinary Action Teams," Journal of Management Studies, 40(6), pp. 1419-1452.
[21] Edmondson, A. C., 2002, Managing the risk of learning: Psychological safety in work teams, Cambridge, MA: Division of Research, Harvard Business School.
[22] Loughry, M. L., Ohland, M. W., and DeWayne Moore, D., 2007, "Development of a Theory-Based Assessment of Team Member Effectiveness," Educational and Psychological Measurement, 67(3), pp. 505-524.
[23] Chhabria, K., Black, E., Giordano, C., and Blue, A., 2019, "Measuring health professions students' teamwork behavior using peer assessment: Validation of an online tool," Journal of Interprofessional Education & Practice, 16.
[24] Hastings, E. M., Jahanbakhsh, F., Karahalios, K., Marinov, D., and Bailey, B. P., 2018, "Structure or Nurture? The Effects of Team-Building Activities and Team Composition on Team Outcomes," Proceedings of the ACM on Human-Computer Interaction, 2(CSCW), pp. 1-21.
[25] Beigpourian, B., 2019, "Using CATME to document and improve the effectiveness of teamwork in capstone courses," Proc. 2019 ASEE Annual Conference and Exposition.
[26] Beigpourian, B., Luchini, F., Ohland, M., and Ferguson, D., "Psychological Safety as an Effective Measurement in Engineering Classrooms," Proc. 2019 ASEE Annual Conference and Exposition.
[27] McNeil, J., Corley, W. B., and Hieb, J. L., "Investigating psychological safety in a flipped engineering course," Proc. 2017 IEEE Frontiers in Education Conference (FIE), IEEE, pp. 1-4.
[28] Edmondson, A. C., Kramer, R. M., and Cook, K. S., 2004, "Psychological safety, trust, and learning in organizations: A group-level lens," Trust and distrust in organizations: Dilemmas and approaches, 12, pp. 239-272.
[29] Kessel, M., Kratzer, J., and Schultz, C., 2012, "Psychological Safety, Knowledge Sharing, and Creative Performance in Healthcare Teams," Creativity and Innovation Management, 21(2), pp. 147-157.
[30] Burningham, C., and West, M. A., 1995, "Individual, Climate, and Group Interaction Processes as Predictors of Work Team Innovation," Small Group Research, 26(1), pp. 106-117.
[31] Paulus, P., 2000, "Groups, teams, and creativity: The creative potential of idea-generating groups," Applied Psychology, 49(2), pp. 237-262.
[32] Massetti, B., 1996, "An Empirical Examination of the Value of Creativity Support Systems on Idea Generation," MIS Quarterly, 20(1), pp. 83-97.

[33] Osburn, H. K., and Mumford, M. D., 2006, "Creativity and Planning: Training Interventions to Develop Creative Problem-Solving Skills," Creativity Research Journal, 18(2), pp. 173-190.
[34] Daly, S. R., Mosyjowski, E. A., and Seifert, C. M., 2014, "Teaching Creativity in Engineering Courses," Journal of Engineering Education, 103(3), pp. 417-449.
[35] Paulus, P. B., and Brown, V. R., 2007, "Toward More Creative and Innovative Group Idea Generation: A Cognitive-Social-Motivational Perspective of Brainstorming," Social and Personality Psychology Compass, 1(1), pp. 248-265.
[36] Toh, C. A., Strohmetz, A. A., and Miller, S. R., 2016, "The Effects of Gender and Idea Goodness on Ownership Bias in Engineering Design Education," Journal of Mechanical Design, 138(10), p. 101105.
[37] Hirsch, W., 2017, "Five questions about psychological safety, answered.," https://scienceforwork.com/blog/psychological-safety/.
[38] Jablokow, K. W., and Kirton, M. J., 2009, Problem solving, creativity, and the level-style distinction, Springer, New York.
[39] Kirton, M. J., 2011, Adaption-Innovation in the Context of Diversity and Change, Routledge, London, UK.
[40] Kirton, M., 1976, "Adaptors and innovators: A description and measure," Journal of Applied Psychology, 61(5), pp. 622-629.
[41] Silk, E. M., Daly, S. R., Jablokow, K. W., Yilmaz, S., Rechkemmer, A., and Wenger, J. M., "Using paradigm-relatedness to measure design ideation shifts," Proc. American Society for Engineering Education (ASEE) Annual Conference.
[42] Silk, E. M., Daly, S. R., Jablokow, K. W., and McKilligan, S., 2019, "Incremental to radical ideas: paradigm-relatedness metrics for investigating ideation creativity and diversity," International Journal of Design Creativity and Innovation, 7(1-2), pp. 30-49.
[43] Heininger, K., Chen, H.-E., Jablokow, K., and Miller, S. R., "How Engineering Design Students' Creative Preferences and Cognitive Styles Impact Their Concept Generation and Screening," Proc. ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.
[44] Amabile, T. M., 1982, "Social psychology of creativity: A consensual assessment technique," Journal of Personality and Social Psychology, 43(5), pp. 997-1013.
[45] Mohammed, S., and Angell, L. C., 2004, "Surface- and deep-level diversity in workgroups: examining the moderating effects of team orientation and team process on relationship conflict," Journal of Organizational Behavior, 25(8), pp. 1015-1039.
[46] Lauring, J., and Selmer, J., 2012, "International language management and diversity climate in multicultural organizations," International Business Review, 21(2), pp. 156-166.
[47] Organ, D. W., 1997, "Organizational Citizenship Behavior: It's Construct Clean-Up Time," Human Performance, 10(2), pp. 85-97.
[48] Singh, B., Winkel, D. E., and 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(2), pp. 242-263.
[49] Tang, S., Nadkarni, S., Wei, L.-Q., and Zhang, S. X., 2020, "Balancing the Yin and Yang: TMT Gender Diversity, Psychological Safety, and Firm Ambidextrous Strategic Orientation in Chinese High-Tech SMEs," Academy of Management Journal.

[50] Lee, H. W., Choi, J. N., and Kim, S., 2018, "Does gender diversity help teams constructively manage status conflict? An evolutionary perspective of status conflict, team psychological safety, and team creativity," Organizational Behavior and Human Decision Processes, 144, pp. 187-199.
[51] Berge, Z. L., 1998, "Differences in teamwork between post-secondary classrooms and the workplace," Education + Training, 40(5), pp. 194-201.
[52] Kinlaw, D. C., 1991, Developing superior work teams.
[53] Blumenfeld, P. C., Marx, R. W., Soloway, E., and Krajcik, J., 1996, "Learning with peers: From small group cooperation to collaborative communities," Educational researcher, 25(8), pp. 37-39.
[54] Fredrick, T. A., 2008, "Facilitating Better Teamwork: Analyzing the Challenges and Strategies of Classroom-Based Collaboration," Business Communication Quarterly, 71(4), pp. 439-455.
[55] Conchie, S. M., Donald, I. J., and Taylor, P. J., 2006, "Trust: Missing Piece(s) in the Safety Puzzle," Risk Analysis, 26(5), pp. 1097-1104.
[56] Baer, M., and Frese, M., 2003, "Innovation is not enough: climates for initiative and psychological safety, process innovations, and firm performance," Journal of Organizational Behavior, 24(1), pp. 45-68.
[57] Furnham, A., 2000, "The Brainstorming Myth," Business Strategy Review, 11(4), pp. 21-28.
[58] Putman, V. L., and Paulus, P., 2009, "Brainstorming, Brainstorming Rules and Decision Making," The Journal of Creative Behavior, 43(1), pp. 29-40.
[59] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2006, "Productivity is not enough: A comparison of interactive and nominal brainstorming groups on idea generation and selection," Journal of Experimental Social Psychology, 42(2), pp. 244-251.
[60] Karau, S. J., and Williams, K. D., 1993, "Social loafing: A meta-analytic review and theoretical integration," Journal of Personality and Social Psychology, 65(4), pp. 681-706.
[61] Reiter-Palmon, R., and Arreola, N. J., 2015, "Does Generating Multiple Ideas Lead to Increased Creativity? A Comparison of Generating One Idea vs. Many," Creativity Research Journal, 27(4), pp. 369-374.
[62] Mirabito, Y., and Goucher-Lambert, K., "The Role of Idea Fluency and Timing on Highly Innovative Design Concepts," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering ConferenceV008T08A035.
[63] Cooper, R. G., and De Brentani, U., 1984, "Criteria for screening new industrial products," Industrial Marketing Management, 13(3), pp. 149-156.
[64] Walumbwa, F. O., and Schaubroeck, J., 2009, "Leader personality traits and employee voice behavior: Mediating roles of ethical leadership and work group psychological safety," Journal of Applied Psychology, 94(5), pp. 1275-1286.
[65] Onarheim, B., and Christensen, B. T., 2012, "Distributed idea screening in stage–gate development processes," Journal of Engineering Design, 23(9), pp. 660-673.
[66] Beggan, J. K., 1992, "On the social nature of nonsocial perception: The mere ownership effect," Journal of Personality and Social Psychology, 62(2), pp. 229-237.

[67] Hill, K. G., and Amabile, T. M., 1993, A social psychological perspective on creativity: Intrinsic motivation and creativity in the classroom and workplace.
[68] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003, "Metrics for measuring ideation effectiveness," Design Studies, 24(2), pp. 111-134.
[69] Nikander, J. B., Liikkanen, L. A., and Laakso, M., 2014, "The preference effect in design concept evaluation," Design Studies, 35(5), pp. 473-499.
[70] Zheng, X., and Miller, S. R., 2019, "Is Ownership Bias Bad? The Influence of Idea Goodness and Creativity on Design Professionals Concept Selection Practices," Journal of Mechanical Design, 141(2), p. 021106.
[71] Mueller, J. S., Melwani, S., and Goncalo, J. A., 2012, "The Bias Against Creativity:Why People Desire but Reject Creative Ideas," Psychological Science, 23(1), pp. 13-17.
[72] Huang, H. Z., Liu, Y., Li, Y., Wang, Z., and Xue, L., 2013, "New evaluation methods for conceptual design selection using computational intelligence techniques," Journal of Mechanical Science and Technology (Online), pp. 733-746.
[73] Zheng, X., Ritter, S. C., and Miller, S. R., 2018, "How Concept Selection Tools Impact the Development of Creative Ideas in Engineering Design Education," Journal of Mechanical Design, 140(5).
[74] Toh, C. A., and Miller, S. R., 2016, "Creativity in design teams: the influence of personality traits and risk attitudes on creative concept selection," Research in Engineering Design, 27(1), pp. 73-89.
[75] Kolodner, J. L., and Wills, L. M., 1996, "Powers of observation in creative design," Design Studies, 17(4), pp. 385-416.
[76] Brereton, M., and McGarry, B., 2000, "An observational study of how objects support engineering design thinking and communication: implications for the design of tangible media," SIGCHI conference on Human Factors in Computing Systems, Association for Computing Machinery, The Hague, The Netherlands, pp. 217–224.
[77] Buchenau, M., and Suri, J. F., 2000, "Experience prototyping," 3rd conference on Designing interactive systems: processes, practices, methods, and techniques, Association for Computing Machinery, New York City, New York, USA, pp. 424–433.
[78] Yang, M. C., 2005, "A study of prototypes, design activity, and design outcome," Design Studies, 26(6), pp. 649-669.
[79] McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., and Vera, A., 2006, "Breaking the fidelity barrier: an examination of our current characterization of prototypes and an example of a mixed-fidelity success," SIGCHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, Montréal, Québec, Canada, pp. 1233–1242.
[80] Pearsall, M. J., and Ellis, A. P. J., 2011, "Thick as thieves: The effects of ethical orientation and psychological safety on unethical team behavior," Journal of Applied Psychology, 96(2), pp. 401-411.
[81] Deng, H., Leung, K., Lam, C. K., and Huang, X., 2019, "Slacking Off in Comfort: A Dual-Pathway Model for Psychological Safety Climate," Journal of Management, 45(3), pp. 1114-1144.

[82] Kirton, M. J., 1984, "Adaptors and innovators—Why new initiatives get blocked," Long Range Planning, 17(2), pp. 137-143.
[83] Vercellone-Smith, P., Jablokow, K., and Friedel, C., 2012, "Characterizing communication networks in a web-based classroom: Cognitive styles and linguistic behavior of self-organizing groups in online discussions," Computers & Education, 59(2), pp. 222-235.
[84] Puccio, G. J., Treffinger, D. J., and Talbot, R. J., 1995, "Exploratory Examination of Relationships Between Creativity Styles and Creative Products," Creativity Research Journal, 8(2), pp. 157-172.
[85] Jablokow, K. W., Teerlink, W., Yilmaz, S., Daly, S. R., and Silk, E. M., 2015, "The Impact of Teaming and Cognitive Style on Student Perceptions of Design Ideation Outcomes," ASEE Conferences, Seattle, Washington.
[86] Samuel, P., and Jablokow, K. W., "Toward an adaption-innovation strategy for engineering design," Proc. International Conference on Engineering Design (ICED11).
[87] Jablokow, K. W., and Booth, D. E., 2006, "The impact and management of cognitive gap in high performance product development organizations," Journal of Engineering and Technology Management, 23(4), pp. 313-336.
[88] Kirton, M. J., and McCarthy, R. M., 1985, "Personal and Group Estimates of the Kirton Inventory Scores," Psychological Reports, 57(3_suppl), pp. 1067-1070.
[89] Clapp, R. G., and De Ciantis, S. M., 1989, "Adaptors and Innovators in Large Organizations: Does Cognitive Style Characterize Actual Behavior of Employees at Work? An Exploratory Study," Psychological Reports, 65(2), pp. 503-513.
[90] Nijstad, B. A., and De Dreu, C. K. W., 2002, "Creativity and Group Innovation," Applied Psychology, 51(3), pp. 400-406.
[91] Fairchild, J., and Hunter, S. T., 2014, "“We've Got Creative Differences”: The Effects of Task Conflict and Participative Safety on Team Creative Performance," The Journal of Creative Behavior, 48(1), pp. 64-87.
[92] Paulus, P. B., and Kenworthy, J. B., 2018, "Overview of team creativity and innovation," Team creativity and innovation., Oxford University Press, New York, NY, US, pp. 11-38.
[93] Boon, A., and Dochy, F., 2016, "“The worst enemy to creativity is team-doubt”. The power of team creative efficacy to foster team processes of learning and creativity, and team effectiveness," Journal of Adult Learning, Knowledge and Innovation JALKI, 1(1), p. 1.
[94] Menold, J., and Jablokow, K., 2019, "Exploring the effects of cognitive style diversity and self-efficacy beliefs on final design attributes in student design teams," Design Studies, 60, pp. 71-102.
[95] Neuman, G. A., Wagner, S. H., and Christiansen, N. D., 1999, "The Relationship between Work-Team Personality Composition and the Job Performance of Teams," Group & Organization Management, 24(1), pp. 28-45.
[96] Mathieu, J. E., Gallagher, P. T., Domingo, M. A., and Klock, E. A., 2019, "Embracing Complexity: Reviewing the Past Decade of Team Effectiveness Research," Annual Review of Organizational Psychology and Organizational Behavior, 6(1), pp. 17-46.

[97] Van der Vegt, G. S., de Jong, S. B., Bunderson, J. S., and Molleman, E., 2010, "Power Asymmetry and Learning in Teams: The Moderating Role of Performance Feedback," Organization Science, 21(2), pp. 347-361.
[98] Buffinton, K. W., Jablokow, K. W., and Martin, K. A., 2002, "Project Team Dynamics and Cognitive Style," Engineering Management Journal, 14(3), pp. 25-33.
[99] McCarthy, R., 1993, "The relationship of individual characteristics of women managers to the pressures experienced at work and choice of coping strategy," University of Hertfordshire.
[100] Linsey, J. S., Wood, K. L., and Markman, A. B., 2008, "Modality and representation in analogy," Artificial Intelligence for Engineering Design, Analysis and Manufacturing : AI EDAM, 22(2), pp. 85-100.
[101] Gonçalves, M., Cardoso, C., and Badke-Schaub, P., 2013, "Inspiration peak: exploring the semantic distance between design problem and textual inspirational stimuli," International Journal of Design Creativity and Innovation, 1(4), pp. 215-232.
[102] Mathieu, J. E., Tannenbaum, S. I., Donsbach, J. S., and Alliger, G. M., 2014, "A Review and Integration of Team Composition Models:Moving Toward a Dynamic and Temporal Framework," Journal of Management, 40(1), pp. 130-160.
[103] Choo, A. S., Linderman, K., and Schroeder, R. G., 2007, "Social and Method Effects on Learning Behaviors and Knowledge Creation in Six Sigma Projects," Manag. Sci., 53(3), pp. 437-450.
[104] Gong, Y., Cheung, S.-Y., Wang, M., and Huang, J.-C., 2012, "Unfolding the Proactive Process for Creativity:Integration of the Employee Proactivity, Information Exchange, and Psychological Safety Perspectives," Journal of Management, 38(5), pp. 1611-1633.
[105] Edmondson, A. C., Bohmer, R. M., and Pisano, G. P., 2001, "Disrupted Routines: Team Learning and New Technology Implementation in Hospitals," Administrative Science Quarterly, 46(4), pp. 685-716.
[106] Kark, R., and Carmeli, A., 2009, "Alive and creating: the mediating role of vitality and aliveness in the relationship between psychological safety and creative work involvement," Journal of Organizational Behavior, 30(6), pp. 785-804.
[107] Takai, S., and Esterman, M., "Towards a Better Design Team Formation: A Review of Team Effectiveness Models and Possible Measurements of Design-Team Inputs, Processes, and Outputs," Proc. ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering ConferenceV003T04A018.
[108] Wilde, D. J., "Using Student Preferences to Guide Design Team Composition," Proc. ASME 1997 Design Engineering Technical ConferencesV003T30A026.
[109] Beigpourian, B., Ferguson, D. M., and Ohland, M. W., "The influence of percentage of female or international students on the psychological safety of team," Proc. FYEE Conference.
[110] Laeser, M., Moskal, B. M., Knecht, R., and Lasich, D., 2003, "Engineering Design: Examining the Impact of Gender and the Team's Gender Composition," Journal of Engineering Education, 92(1), pp. 49-56.

[111] Okudan, G. E., and Bilén, S. G., 2003, "Effect Of Gender Orientation Of The Design Task On Team Performance: A Preliminary Study," 2003 Annual ASEE Conference, ASEE, Nashville, Tennessee.
[112] Pearsall, M. J., Ellis, A. P. J., and Evans, J. M., 2008, "Unlocking the effects of gender faultlines on team creativity: Is activation the key?," Journal of Applied Psychology, 93(1), pp. 225-234.
[113] Dos Santos, L. M., 2021, "Female Mechanical Engineering Students' Career Decisions and Development: A Case Study of University Undergraduate Students," Journal of Educational and Social Research, 11(3), p. 1.
[114] Hatmaker, D. M., 2013, "Engineering Identity: Gender and Professional Identity Negotiation among Women Engineers," Gender, Work & Organization, 20(4), pp. 382-396.
[115] Dasgupta, N., Scircle, M. M., and Hunsinger, M., 2015, "Female peers in small work groups enhance women's motivation, verbal participation, and career aspirations in engineering," Proceedings of the National Academy of Sciences, 112(16), pp. 4988-4993.
[116] Mohan, G., and Lee, Y., 2019, "Temporal Dynamics of Collective Global Leadership and Team Psychological Safety in Multinational Teams: An Empirical Investigation," Advances in Global Leadership, Emerald Publishing Limited, pp. 29-47.
[117] Liu, Y., Keller, R. T., and Bartlett, K. R., 2021, "Initiative climate, psychological safety and knowledge sharing as predictors of team creativity: A multilevel study of research and development project teams," Creativity and Innovation Management, 30(3), pp. 498-510.
[118] Zhang, Y., Fang, Y., Wei, K.-K., and Chen, H., 2010, "Exploring the role of psychological safety in promoting the intention to continue sharing knowledge in virtual communities," International Journal of Information Management, 30(5), pp. 425-436.
[119] Ou, A. Y., Waldman, D. A., and Peterson, S. J., 2018, "Do Humble CEOs Matter? An Examination of CEO Humility and Firm Outcomes," Journal of Management, 44(3), pp. 1147-1173.
[120] Blau, P. M., 1977, Inequality and heterogeneity: A primitive theory of social structure, Free Press, New York.
[121] González-Moreno, Á., Díaz-García, C., and Sáez-Martínez, F. J., 2018, "R&D team composition and product innovation: Gender diversity makes a difference," European Journal of International Management, 12(4), pp. 423-446.
[122] Rentsch, J. R., and Klimoski, R. J., 2001, "Why do 'great minds' think alike?: antecedents of team member schema agreement," Journal of Organizational Behavior, 22(2), pp. 107-120.
[123] Andrews, P. H., 1992, "Sex and Gender Differences in Group Communication:Impact on the Facilitation Process," Small Group Research, 23(1), pp. 74-94.
[124] Hawkins, K., and Power, C. B., 1999, "Gender Differences in Questions Asked During Small Decision-Making Group Discussions," Small Group Research, 30(2), pp. 235-256.

[125] Connelly, C. E., and Kevin Kelloway, E., 2003, "Predictors of employees' perceptions of knowledge sharing cultures," Leadership & Organization Development Journal, 24(5), pp. 294-301.
[126] van Ginkel, W. P., and van Knippenberg, D., 2008, "Group information elaboration and group decision making: The role of shared task representations," Organizational Behavior and Human Decision Processes, 105(1), pp. 82-97.
[127] Foor, C. E., Walden, S. E., and Trytten, D. A., 2007, ""I Wish that I Belonged More in this Whole Engineering Group:" Achieving Individual Diversity," Journal of Engineering Education, 96(2), pp. 103-115.
[128] Lee, M. J., Collins, J. D., Harwood, S. A., Mendenhall, R., and Huntt, M. B., 2020, ""If you aren't White, Asian or Indian, you aren't an engineer": racial microaggressions in STEM education," International Journal of STEM Education, 7(1), pp. 1-16.
[129] Camacho, M. M., and Lord, S. M., ""Microaggressions" in engineering education: Climate for Asian, Latina and White women," Proc. 2011 Frontiers in Education Conference (FIE), pp. 1-6.
[130] Amabile, T. M., 1983, "The social psychology of creativity: A componential conceptualization," Journal of Personality and Social Psychology, 45(2), pp. 357-376.
[131] Miller, S. R., Hunter, S. T., Starkey, E., Ramachandran, S. K., Ahmed, F., and Fuge, M., 2020, "How should we measure creativity in engineering design? A Comparison of social science and engineering approaches (DETC2020-22446)," Journal of Mechanical Design, pp. 1-16.
[132] Amabile, T. M., 1996, Creativity in Context: Update to the Social Psychology of Creativity, Westview Press, Boulder, CO.
[133] Cropley, D. H., Kaufman, J. C., and Cropley, A. J., 2011, "Measuring creativity for innovation management," Journal of Technology Management & Innovation, 6(3), pp. 13-30.
[134] Horn, D., and Salvendy, G., 2009, "Measuring consumer perception of product creativity: Impact on satisfaction and purchasability," Human Factors and Ergonomics in Manufacturing & Service Industries, 19(3), pp. 223-240.
[135] Amabile, T. M., 1983, "Brilliant but cruel: Perceptions of negative evaluators," Journal of Experimental Social Psychology, 19(2), pp. 146-156.
[136] Kaufman, J. C., Baer, J., Cropley, D. H., Reiter-Palmon, R., and Sinnett, S., 2013, "Furious activity vs. understanding: How much expertise is needed to evaluate creative work?," Psychology of Aesthetics, Creativity, and the Arts, 7(4), pp. 332-340.
[137] Nagasundaram, M., and Bostrom, R. P., 1994, "The Structuring of Creative Processes Using GSS: A Framework for Research," Journal of Management Information Systems, 11(3), pp. 87-114.
[138] Dean, D. L., Hender, J., Rodgers, T., and Santanen, E., 2006, "Identifying good ideas: constructs and scales for idea evaluation," Journal of Association for Information Systems, 7(10), pp. 646-699.
[139] Puccio, G. J., and Chimento, M. D., 2001, "Implicit Theories of Creativity: Laypersons' Perceptions of the Creativity of Adaptors and Innovators," Perceptual and Motor Skills, 92(3), pp. 675-681.

[140] Talbot, R. J., 1997, "Taking Style On Board (or how to get used to the idea of creative adaptors and uncreative innovators)," Creativity and Innovation Management, 6(3), pp. 177-184.
[141] Grace, K., and Maher, M. L., "Surprise and reformulation as meta-cognitive processes in creative design," Proc. Proceedings of the Third Annual Conference on Advances in Cognitive Systems, Cognitive Systems Foundation, p. 8.
[142] Sarkar, P., and Chakrabarti, A., 2014, "Ideas generated in conceptual design and their effects on creativity," Research in Engineering Design, 25(3), pp. 185-201.
[143] Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2021, "The Crowd Predicts a Paradigm Shift: Exploring the Relationship Between Cognitive Style and the Paradigm-Relatedness of Design Solutions," Proc. ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers.
[144] Tekmen-Araci, Y., and Mann, L., 2019, "Instructor approaches to creativity in engineering design education," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233(2), pp. 395-402.
[145] Joshi, A., 2014, "By Whom and When Is Women's Expertise Recognized? The Interactive Effects of Gender and Education in Science and Engineering Teams," Administrative Science Quarterly, 59(2), pp. 202-239.
[146] Hirshfield, L., and Koretsky, M. D., 2018, "Gender and Participation in an Engineering Problem-Based Learning Environment," Interdisciplinary Journal of Problem-Based Learning, 12(1), pp. 1-18.
[147] Ehrlenspiel, K., and Dylla, N., 1993, "Experimental Investigation of Designers' Thinking Methods and Design Procedures," Journal of Engineering Design, 4(3), pp. 201-212.
[148] Borghans, L., Heckman, J. J., Golsteyn, B. H., and Meijers, H., 2009, "Gender differences in risk aversion and ambiguity aversion," Journal of the European Economic Association, 7(2-3), pp. 649-658.
[149] Charyton, C., and Merrill, J. A., 2009, "Assessing general creativity and creative engineering design in first year engineering students," Journal of Engineering Education, 98(2), pp. 145-156.
[150] Cropley, D. H., and Cropley, A. J., 2000, "Fostering creativity in engineering undergraduates," High Ability Studies, 11(2), pp. 207-219.
[151] Cropley, D. H., 2016, "Creativity in Engineering," Multidisciplinary Contributions to the Science of Creative Thinking, G. E. Corazza, and S. Agnoli, eds., Springer Singapore, Singapore, pp. 155-173.
[152] Thompson, G., and Lordan, M., 1999, "A review of creativity principles applied to engineering design," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 213(1), pp. 17-31.
[153] Wynn, A. T., and Correll, S. J., 2018, "Combating Gender Bias in Modern Workplaces," Handbook of the Sociology of Gender, B. J. Risman, C. M. Froyum, and W. J. Scarborough, eds., Springer International Publishing, pp. 509-521.

[154] Lorelle, A. M., and Denise, S., 2013, "The Influence of Gender Stereotypes on Role Adoption in Student Teams," 2013 ASEE Annual Conference & Exposition, ASEE Conferences, Atlanta, Georgia.
[155] Junge, D., and Leckart, S., 2020, "Challenger: The Final Flight," Netflix, USA.
[156] Werhane, P. H., 1991, "Engineers and management: The challenge of the challenger incident," Journal of Business Ethics, 10(8), pp. 605-616.
[157] Roberto, M. A., 2002, "Lessons from Everest: The interaction of cognitive bias, psychological safety, and system complexity," California Management Review, 45(1), pp. 136-158.
[158] Walton, G. M., and Cohen, G. L., 2007, "A question of belonging: Race, social fit, and achievement," Journal of Personality and Social Psychology, 92(1), pp. 82-96.
[159] Walton, G. M., Murphy, M. C., and Ryan, A. M., 2015, "Stereotype threat in organizations: Implications for equity and performance," Annual Review of Organizational Psychology and Organizational Behavior, 2, pp. 523-550.
[160] Tapia, A. H., and Kvasny, L., 2004, "Recruitment is never enough: retention of women and minorities in the IT workplace," Proceedings of the 2004 SIGMIS conference on Computer personnel research: Careers, culture, and ethics in a networked environment, Association for Computing Machinery, Tucson, AZ, USA, pp. 84–91.
[161] Waldrop, M. M., 1986, "The Challenger Disaster: Assessing the Implications," Science, 231(4739), pp. 661-663.
[162] Hon, A. H. Y., Bloom, M., and Crant, J. M., 2014, "Overcoming Resistance to Change and Enhancing Creative Performance," Journal of Management, 40(3), pp. 919-941.
[163] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2007, "Relative accessibility of domain knowledge and creativity: The effects of knowledge activation on the quantity and originality of generated ideas," Journal of Experimental Social Psychology, 43(6), pp. 933-946.
[164] Hillygus, D. S., and Snell, S. A., 2015, "Longitudinal surveys: Issues and opportunities," Oxford handbook on polling and polling methods, pp. 28-52.

DISSERTATION PUBLICATIONS

Journal Articles

Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, "Does Psychological Safety Impact Team Productivity and Effectiveness During Concept Development? An Exploration in Engineering Design Education," Journal of Mechanical Design.

Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., Submitted 2022, "An Exploration of the Relationships Between Cognitive Style, Psychological Safety, and the Paradigm-Relatedness of Design Solutions in Engineering Design Teams in Education," Journal of Mechanical Design.

Conference Papers

Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2021, "How Engineering Design Students' Psychological Safety Impacts Team Concept Generation and Screening Practices," Proc. ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Virtual.

Cole, C., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., 2021, "The Crowd Predicts a Paradigm Shift: Exploring the Relationship Between Cognitive Style and the Paradigm-Relatedness of Design Solutions," Proc. ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Virtual.

Cole, C., Jablokow, K., Mohammed, S., and Miller, S., In Press 2022, “The Impact of Gender on Individual Perceptions and Team Psychological Safety in Engineering Design Teams,” Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, St. Louis, Missouri, USA.

Other Significant Publications

Cole, C., O’Connell, A., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, “What Factors Impact Psychological Safety in Engineering Student Teams? A Mixed-Method Longitudinal Investigation,” Journal of Mechanical Design.

Cole, C., O’Connell, A., Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, “How Long Until We Are (Psychologically) Safe? A Longitudinal Investigation of Psychological Safety in Virtual Engineering Design Teams in Education,” Tenth International Design Computing and Cognition Conference, Glasgow, Scotland.

O’Connell, A., **Cole, C.**, Marhefka, J., Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, “Can I Get a Word In? the Impact of Turn-Taking and Gender on Engineering Design Students’ Psychological Safety,” Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, St. Louis, Missouri, USA.

Drum, A., **Cole, C.**, Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, “Let’s Role Play! The Impact of Video Frequency and Role Play on the Utility of a Psychological Safety Team Intervention,” Proc. ASME 2022 International Design

Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, St. Louis, Missouri, USA.

Scarpinella, S., **Cole, C.**, Jablokow, K., Mohammed, S., Ritter, S., and Miller, S., In Press 2022, “Can We Get an Intervention, Please? The Utility of Teaming Interventions on Engineering Design Student Psychological Safety,” Proc. ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, St. Louis, Missouri, USA.

VITA

Courtney Cole

Industrial and Manufacturing Engineering
The Pennsylvania State University cmc6303@psu.edu
University Park, PA 16802

Education

M.S. Industrial Engineering, The Pennsylvania State University, 2020

B.S. Mechanical Engineering, Penn State Erie, The Behrend College, 2019

Research Interests

- Psychological safety in engineering design teams
- Preferences for problem-solving in engineering design teams
- Problem-solving and decision making in high-risk scenarios