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HOW ENGINEERING DESIGN STUDENTS' PSYCHOLOGICAL SAFETY IMPACTS TEAM CONCEPT GENERATION AND SCREENING PRACTICES

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ABSTRACT

Psychological safety has been shown to be a consistent, generalizable, and multilevel predictor of outcomes in performance and learning across fields. While work in this field has suggested 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 fostering psychological safety in a team environment is most important. This study provides the first attempt at answering this question through an empirical study with 53 engineering design student teams over the course of a 4- and 8-week design project. 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 not related to the number of ideas a team developed, it was positively related to the quality (goodness) of the ideas developed. In addition, while no relationship was found between psychological safety and ownership bias during concept screening, the results showed that teams with high psychological safety selected a higher percentage of their team members ideas.

Keywords: design theory and methodology, design theory, decision making

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. 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 have integrated teaming as a key aspect of their core business strategy [2, 3], it is unclear what characteristics of a team make them most effective.

In order 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 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 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]. Instead, Google's data indicated that *psychological safety*, more than anything else, was critical to making the team work.

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]. 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* [8]. This is the very description of the skills needed in the *engineering design process* [9, 10]. However, there has been 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]. These results indicate there may be a 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 [13], contains themes of psychological safety [14, 15]. However, research on this tool has only speculated about the role of psychological safety in undergraduate engineering team student projects [16-18]. Finally, while our own prior work has validated the longitudinal reliability of psychological safety in an engineering student sample [9], there has 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 student performance in the conceptual phases of the engineering design process. The results of this study provide empirical evidence of the role of psychological safety on engineering student team outputs. As such, these results can be used to identify *when* psychological safety is important and drive research on *what types* of interventions may be useful for fostering team psychological safety in engineering.

RELATED LITERATURE

In its simplest form, the engineering design process consists of three phases: generation, evaluation (e.g., concept screening), and communication [19-21]. During *concept generation,* teams seek to develop creative ideas, or those that are both novel and useful [22]. 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 [23].

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 [19]. While such conflict has been shown to hold value in terms of problem-solving [24, 25], prior work has also shown that such conflict is only beneficial if the psychological safety of the team is high, allowing members to tactfully speak out against potential issues [6, 11]. For example, low levels of psychological safety can hinder 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 [26]. In addition, research in hierarchies of hospital workers communicating through intense, unpredictable contexts [11], as well as cardiac departments trying to learn new technologies [27], 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, 28]. 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]. While outside the context of engineering, research has also linked psychological safety to employees' feelings of vitalities and ultimately their involvement in creative work [29].

In addition to this empirical work, reviews of the psychological safety literature have also 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 has shown that teams with low psychological safety refrained from sharing novel ideas in their team [30]. 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 and the number of ideas, or the fluency of ideas, a team develops [31, 32]. In addition, 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 [11, 12, 28]. However, while feeling interpersonally safe to generate novel ideas may help overcome the fear of risk-taking [6, 12, 28], it does not necessarily guarantee that team members can overcome barriers to brainstorming in groups [33]. 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 [33]. Or, "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 [34]. Therefore, these types of group brainstorming issues can hinder performance if they happen to override high team psychological safety.

Psychological safety may also play an important role in the *concept screening* stage of the engineering design process. In fact, it is thought that higher psychological safety is correlated with a higher level of agreeableness amongst team members [35], 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 toward their own ideas, an effect known as ownership bias [36, 37], during concept screening due to the relationship between psychological safety, trust, and openness of communication [38]. On the other hand, 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 [39]. This is because the idea rater views that other members produce higher quality designs for the design tasks in comparison to their own [39]. While prior work has demonstrated the effects of ownership bias [40], recent work on an engineering sample identified that ownership bias may only be present when taking into account the quality, or a term they referred to as "goodness", of the idea [41]. Thus, the relationship between psychological safety and ownership may be mediated by such quality measurements. In addition, because "goodness" of an idea is judged by other team members, judgements of idea "goodness" may be effected by psychological safety. This is because prior work has shown that risk aversion can occur when team psychological safety is low [6], and there is a link between team member risk aversion and creative concept generation and selection [42]. The relationship between risk aversion and creativity has been attributed to the fact that creative concepts are considered a high-risk undertaking [41, 43]. 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" ([44] p. 48) because creative ideas must not only be generated for innovation to occur, but must also be selected throughout the engineering design process.

If a relationship between psychological safety and engineering outputs is established, the question then becomes how do we foster this in engineering teams. This is important because research has shown that implementing psychological safety intervention can be beneficial to improving team success in areas such healthcare [30], manufacturing [6], geographical dispersion [45], innovation [46], user interface design courses [15], and software development [47]. However, before such interventions can be developed, a relationship between psychological safety and engineering outputs must be established. In addition, we must identify *when* or *to what effect* psychological safety impacts the different phases of the design process in order to pinpoint where interventions would be most beneficial.

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 an engineering context. As such, the current investigation was developed to explore the role of team psychological safety on student performance in the conceptual phases of the engineering design process.

RESEARCH OBJECTIVES

The main objective 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 more designs to choose from [48]. This is because psychological safety has been shown to facilitate the contribution of ideas [7] and encourages people to take initiative to develop new products and services [49]. 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 [50].

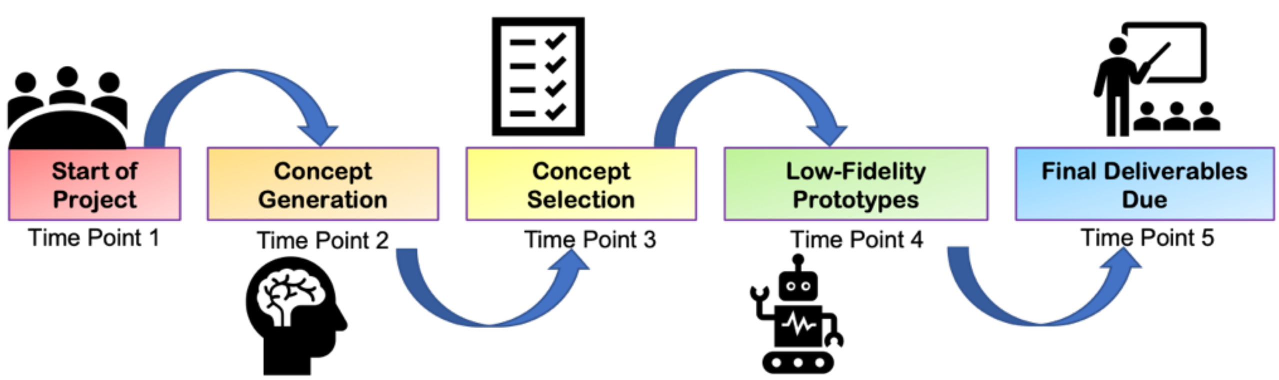


Figure 1: Study timeline – psychological safety was captured at the end of each time point (total time period: 8 weeks for Fall/Spring, 4 weeks for Summer)

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. Since 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 [39, 41], causing them to lose sight of the importance of collaboration [51]. 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 [41].

METHODOLOGY

In an effort 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 Fall and Spring of 2019, and the second summer term of 2018 and 2019. Figure 1 depicts the study timeline. These time points were chosen because they represent milestones in the engineering design process for a team [19], 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.

TABLE 1: DESCRIPTIONS OF DESIGN CHALLENGES BASED ON INSTRUCTOR AND SEMESTER

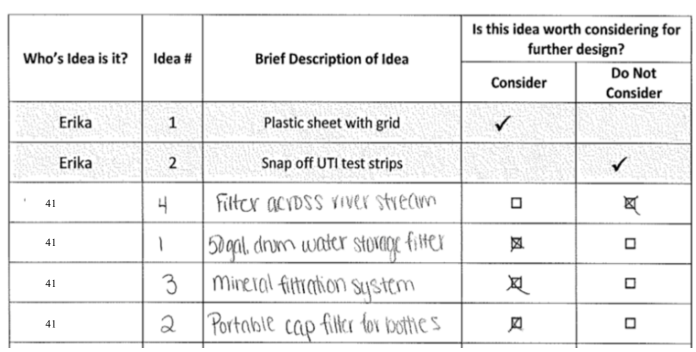
Semester	Instructor	Sample Size (n)	Project Description
Summer 2018	A	48 students; 12 teams	Tackle food insecurity in developing countries as a result of climate, conflict, unstable markets, food waste, and lack of investment in agriculture.
Spring 2019	A and B	49 students; 13 teams	Ensure healthy lives 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.

Participants

Fifty-three engineering design student teams, comprised of 207 participants (151 males and 56 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.

Procedure

The study was completed over the course of two years with a first-year cornerstone engineering design class. Specifically, eight sections of this course were studied in the current investigation; five 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 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 instantiations of the course (see Table 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. Importantly, at the end of each time point, students completed an electronically delivered seven-question psychological safety survey developed by Edmondson [6]. 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 [52]. A popular example of one of these questions is, "If you make a mistake on this team, it is often held against you" [6]. 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



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		✓
41	4	Filter across river stream	☐	☒
41	1	50gal drum water storage filter	☒	☐
41	3	Mineral filtration system	☒	☐
41	2	Portable cap filter for bottles	☒	☐

Figure 2: Example of the concept screening sheet for each team member

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 to determine their cognitive styles; KAI theory has been validated across the general population and other sub-populations, including engineers [53, 54]. 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 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.

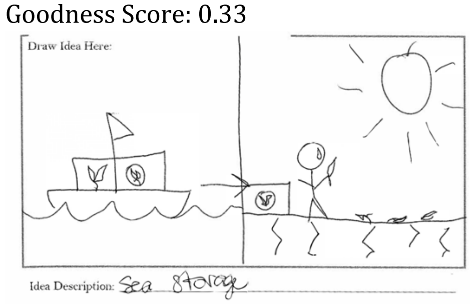
During ***Time Point 2***, students attended a lecture on customer needs and developed their problem statements. After this, an innovation lesson that focused on the importance of creativity in engineering design was completed. Next, the participants were guided through a series of idea generation exercises where they were asked to individually sketch as many ideas as possible in a 15-minute session. 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.

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

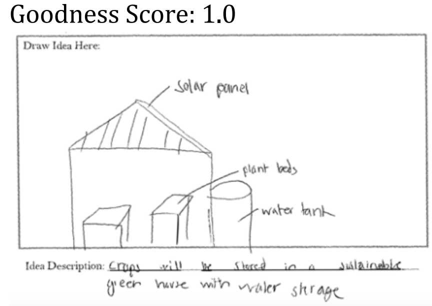
TABLE 2: EXAMPLES OF IDEAS GENERATED WITH GOODNESS SCORES FOR EACH DESIGN PROBLEM

Food Insecurities

Goodness Score: 0.33

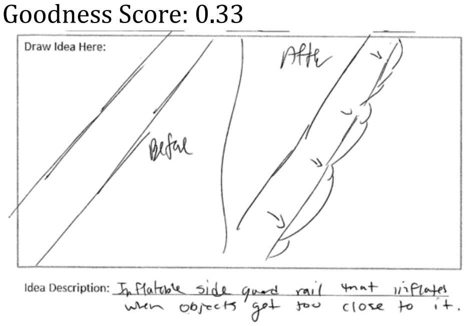


Goodness Score: 1.0

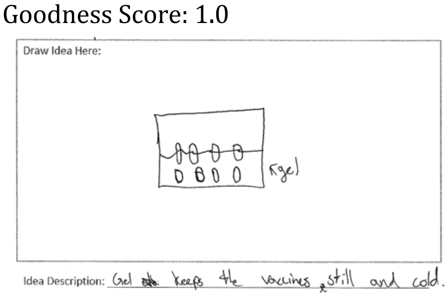


Healthy Living

Goodness Score: 0.33

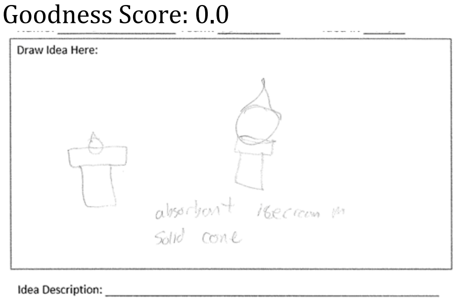


Goodness Score: 1.0

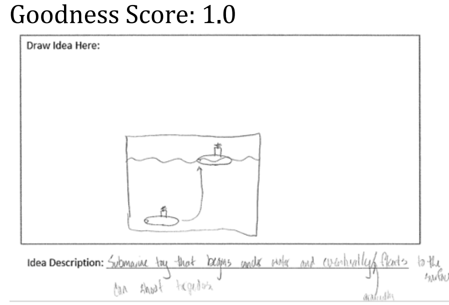


Novel Water Toy

Goodness Score: 0.0



Goodness Score: 1.0



Not Consider" categories (see Figure 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 ideas 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 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 computer-aided design (CAD) rendering of the design. After all groups presented their presentations, students completed the fifth and final psychological safety survey.

METRICS

To answer our 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 [32] 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*. Specifically, it was calculated as follows:

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

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*. In order to calculate this, a custom MATLAB code was developed to make the process more efficient.

Individual Perceptions of Idea Goodness: Idea goodness was developed by Toh et al. [39] to rate the quality or effectiveness of an idea [55] by aggregating the opinions of team members. As opposed to a scoring method that relies on expert raters that are typically more knowledgeable [56], 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. In order 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:

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

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 [39]. 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. In order 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 [41]. In order to measure ownership bias, the continuous parameter idea goodness was applied to six distinct metrics to analyze the continuous parameter of % 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 % 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:

% of own ideas selected

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

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.

% of own ideas with goodness score above 0.5 selected

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

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.

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

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

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.

% of team members' ideas selected

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

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.

Team Psychological Safety: Psychological safety on the team level is defined as the team's belief that they are safe for interpersonal risk taking [6]. This team consensus is quantified by using individual psychological safety scores of each team member and taking the average of all scores at each time point. From there, interrater agreement must be checked to ensure consistency across the individual responses [57]. Specifically, the calculation for the team psychological safety score is:

$$team\ psychological\ safety = \frac{\sum_{i=1}^{K} X_{i,j}}{K} \qquad (7)$$

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

RESULTS AND DISCUSSION

During the study, the 53 engineering design teams generated an average of 27.42 ± 7.83 ideas. In addition, teams selected an average of 69.04 ± 10.99% of the ideas generated. In order 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. 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. Controlling for KAI was found to be statistically insignificant, with adjusted $R^2 = -.019$, and $F(1, 51) = .021$, $p = .886$. 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 [58].

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

The objective 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 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 [49]. Furthermore, because idea goodness may tap into feelings of trust within the team and influence an increase in psychological safety [50], 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 ($r_{wg} = 0.87$, ICC(1) = 0.17, ICC(2)=0.44) [57]. This is based on the criteria defined in LeBreton and Senter (2008) [57], 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. The results of the regression analysis failed to reveal a statistically significant relationship between these variables, $F(1, 52) = 2.273$, $p = 0.138$. This finding refuted our hypothesis; psychological safety was not shown to facilitate the contribution of ideas, despite prior research on this effect [7].

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, $F(1, 52) = 11.785$, $p < .001$. Specifically, psychological safety accounted for 18.8% of the explained variance in idea goodness. The regression equation was: predicted idea goodness = 0.130 + 0.092x (psychological safety). This finding confirmed our hypothesis 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 [35].

Whereas psychological safety was not found to be associated with the total number of ideas generated per team, it was associated with more viable ideas. This result indicates that as psychological safety increased, so did the average idea goodness of the team. Since psychological safety impacts the team's likelihood to take risks [6], rating others' ideas highly could be a way 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 [28], where higher trust in team members' abilities can promote risk-taking in the form of selecting others' ideas.

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

The objective of our second research question was to examine if a relationship existed between team psychological safety and performance during *concept screening*. Specifically, we hypothesized that as team psychological safety decreased, the incidence of ownership bias would increase because ownership bias relates to a loss of sense in the importance of collaboration [51]. Furthermore, we hypothesized that as perceptions of psychological safety decreased at the individual level, incidence of ownership bias would increase [48].

Similar to in 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} = 0.88, ICC(1) = 0.14, ICC(2)=0.38) [57]. 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 [59]. Four of the six cases are described here, where the remaining two analyses were variations of % of team members' ideas selected, similar to that of the idea goodness cutoffs used in *% of own ideas selected*.

The first linear regression used the independent variable of psychological safety during *Time Point 3, concept screening*, and the dependent variable *% of own ideas selected*. The results failed to show a statistically significant relationship between psychological safety and % of own ideas selected, $F(1, 52) = 1.41$, $p = 0.24$. To see if this ownership bias was contingent on the quality of the ideas, a second linear regression analysis used the dependent variable was *% own ideas with goodness score below 0.5*. However, the results failed to reveal a statistically significant correlation, $F(1, 52) = 0.05$, $p = .83$. Finally, a third linear regression analysis was conducted with *% own ideas with goodness score above 0.5.* However, the results again revealed no statistically significant relationship, $F(1, 52) = 2.27$, $p = 0.14$. The final linear regression analysis used the dependent variable of *% of team members' ideas selected* revealed a statistically significant correlation, $r(52) = .34$, $p = .01$. This model established that psychological safety significantly predicted the % of team members' ideas selected, $F(1, 52) = 6.62$, $p = .01$, and psychological safety accounted for 9.8% of the explained variability in the % team members' ideas selected. A scatterplot of this is shown in Figure 3. More specifically, as psychological safety increased by one unit, the percentage of team ideas selected increased by .017963 units, ϒ10=-0.017963, t = .924, $p = .357$.

These results refute our hypothesis in the sense that ownership bias is not associated with lower team psychological safety nor individual perceptions of psychological safety due to the lack of statistical significance. In fact, the halo effect is more prominent than anything else, where team members tend to select others' ideas over their own [39]. This is exhibited where a higher team psychological safety score is associated with a higher percentage of team members' ideas being selected, as shown in Figure 3. Furthermore, analysis of psychological safety through individual perceptions shows that in every case except for the percentage of team members' ideas selected, the lack of statistical significance shows that ownership bias cannot be detected on an individual basis. Nevertheless, since the psychological safety scale points to being able to take risks among others in social interactions [6], these results imply that team members feel it is safe to select others' ideas without the fear of being penalized.

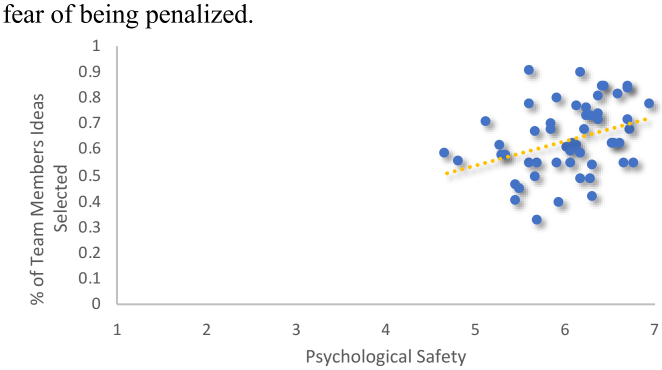


Figure 3: The average percentage of team members' ideas selected as a function of Psychological Safety (PS) at *Time Point 3*, F(1, 52) = 6.62, *p* = .01

DISCUSSION

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

- Psychological safety was not correlated with the number of ideas (fluency) produced by a team.
- Psychological safety was significantly and positively related to team idea goodness.
- Ownership bias was not correlated with both the team level psychological safety and individual perceptions

of psychological safety in all cases except for the % of team members' ideas selected.

The finding that psychological safety was not significantly related to the total number of ideas generated (fluency) by the team aligns with research indicating that individuals perform better with brainstorming tasks than teams [60]. While some prior research found that when members generate ideas in a team, they tend to offer more ideas in comparison to working individually [44], this wasn't the case in our study. This could be due to the fact that other factors may bear more weight in this process, such as other barriers to brainstorming, such as production blocking and social loafing [33]. Although feeling interpersonally safe to generate novel ideas may overcome the evaluation apprehension or fear of being judged and looking unintelligent [6, 12, 28], it does not necessarily override previously mentioned barriers to brainstorming in groups [33]. This can be seen where production blocking allows only one person to speak at a time [33], and individuals do not hold themselves accountable as a result of social loafing [34]. However, the ideas generated during the concept generation stage tended to be of higher subjective quality based on the idea goodness ratings [39]. Since idea goodness can be facilitated by feelings of trust within the team, this may have influenced psychological safety in a positive manner [50], and thus idea goodness also increased.

In contrast to the majority of *concept generation*, psychological safety positively influenced the *concept screening* stage. 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 [39], as demonstrated in these study results. In the creative process of engineering design [61], *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 [39, 41]. However, there was no statistically significant correlation, exhibiting that ownership bias and psychological safety were not strongly related. In fact, the positive significance of the % of team members' ideas being selected during *concept screening* shows that teams showed more signs of agreeableness in selecting others' ideas when psychological safety was higher [35]. This is opposed to individuals selecting more of their own ideas with low idea goodness when psychological safety was lower.

One conclusion of our results is that psychological safety exerts differential effects on creative processes. For example, psychological safety was found to be unrelated to idea fluency during *concept generation*, but it was significantly associated with idea goodness during the *concept screening*. Furthermore, psychological safety was found to be impactful for the % of team members' ideas selected during the examination of ownership bias during *concept screening*, meaning that higher psychological safety results in team members selecting a higher percentage of others' ideas; the halo effect [39].

STUDY LIMITATIONS, CONCLUSION, AND FUTURE WORK

While we understand that other work in the field of team interaction has been thoroughly researched [62], our intention is to focus on how psychological safety impacts team interactions. Furthermore, 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. In addition, according to previous work related to creativity [22], other individual qualities can influence or inhibit their creativity. Since 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. Furthermore, the lack of team interaction at such an early stage in the design process may contribute to the outcome of no correlation, since 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 [41]. That being said, the idea goodness ratings in this study were simplified in comparison to an earlier study [41], which may be why very good ideas were not rated as highly, and very poor ideas were not rated as negatively. Since these analyses rely on definitions from Toh et al. [39] 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, since 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 [39], 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, since 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, unique and potentially successful ideas could be lost due to an adaptive mindset; doing things on the cusp of the problem constraints can be unsettling to more adaptive individuals, so they may not give these ideas a chance [53, 54]. While results are more in favor of the risk-taking aspect, further analysis is needed to ensure that this is the case.

Building on the limitations presented in the idea goodness ratings, although idea goodness through non-expert ratings has been validated in other studies [39, 41], we understand that individual perceptions of an idea's quality can be subjective. In order to take a more objective approach, expert ratings for idea creativity can be utilized [63], and then adapted to an engineering design setting [64]. From there, results from the Consensual Assessment Technique (CAT) [63] can be used in analyses with team psychological safety.

In addition to specific limitations in *concept generation* and *concept screening*, the causal direction should be discussed as well. Since 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, which usually only lasted for at most, half of each class session. 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, such as working on assignments or studying together [65], 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, while we do not clearly know the causal direction, it is beneficial to understand how psychological safety impacts team engineering design outputs.

Along with the 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 we agree that these outputs could 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 the outputs. Further investigation of the potential impact of cognitive style (via KAI) on psychological safety might still be useful, but we are reserving it for future iterations of this research.

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 in order 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). Furthermore, although performance 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 [66]. 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 [67] during these time points is important in determining how the interactions impact students' abilities to perform optimally relative to their ability during *concept generation* and *concept screening*.

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