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Investigating Student Perceptions of Team-based Brainstorming During Conceptual Design: Challenges and Recommendations

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Introduction

Brainstorming during engineering design is a crucial component of engineering education. Diverse brainstorming skills allows students to generate multitudes of ideas, subsequently opening more avenues to novel and innovative solutions. However, brainstorming comes in many forms and with a range of challenges. And while scholars have offered recommendations for strategies to optimize idea generation and exploration of the design space, less work has explored student perceptions of brainstorming processes more broadly. We are interested in student perspectives because they can offer insight into the ways ideation can be tailored to student needs and thus improve idea sharing and generation (i.e., brainstorming effectiveness). The purpose of this research is to explore challenges students face while brainstorming as well as recommendations they have for addressing those challenges. To that end, we pose the following research questions:

> *RQ1: How do students describe significant challenges they encounter during brainstorming sessions?*
> *RQ2: What do students recommend to improve brainstorming processes?*

To investigate these questions, we conducted focus groups in which engineering students recounted and reflected on their experiences from a brainstorming session. We emphasize their insight on obstacles encountered and recommendations to overcome these challenges. This research therefore offers a student-centered viewpoint on the issues in engineering education that might hinder students' brainstorming abilities or prevent full exploration of the design space. By exploring these topics, we hope to offer recommendations for more effectively incorporating brainstorming practices into engineering education in ways that better suit student needs.

In the following sections, we review literature concerning various design processes, ideation challenges, and recommendations for increasing creative output. Next, we outline our methods for data collection and analysis. Lastly, we provide an overview of our findings as it pertains to the challenges that subjects within the ideation study faced and their recommendations for better ideation. The implications of these findings are relevant to engineering educators, researchers, and curriculum designers to enable more effective ideation sessions in the classroom.

Literature Review

Idea Generation and Brainstorming Environment

Brainstorming is the most common method of idea generation and is prevalent in professions within and outside of engineering disciplines. In general, the brainstorming process can be distilled to three critical actions: generating, editing/organizing, and evaluating ideas [1]. There are many established methods of brainstorming, such as traditional group brainstorming; however, they come with limitations (e.g., social-loafing, evaluation apprehension, group dynamics, etc.) [2]. To examine some of these limitations, research by Osborn used focus groups to examine different approaches for idea generation [3]. His findings suggest a correlation between idea quantity and quality and that both metrics increase in more playful environments and as group members 'warmed up' to the activity. This research shows the importance of how the environment is conducive to allowing ideas to flow freely and for team members to be comfortable sharing ideas in a variety of mediums as they arise.

The two most common forms of brainstorming are group and nominal (i.e., individual) brainstorming. In a study conducted by Bouchard and Hare (1970), researchers compared nominal and group brainstorming processes based on their ability to produce non-redundant ideas [4]. Results indicated that while large groups tend to have more interaction, nominal samples actually generated more novel ideas. These results are supported by Gallupe, Bastianutti, & Cooper (1991), who found that brainstorming groups produced fewer ideas than nominal brainstormers, which he attributed to factors such as social-loafing, evaluation apprehension (i.e., participants withholding ideas out of concern for negative appraisals), and production blocking within the groups.

Researchers have also explored the impacts of electronic group brainstorming (i.e., idea generation when conducted with anonymous participants through some kind of computer medium) [1], [5], [6]. Their work found that anonymity can be advantageous and might improve productivity and creativity. Since participants were anonymous, they were less reluctant to share ideas due to the fact that other members could not identify who submitted them. Another method for improving group brainstorming is the use of divergent thinking frameworks that blend group and nominal brainstorming methods. One example is the 6-3-5 brainstorming method, which involves silent, individual—yet collaborative—brainstorming [7]. The approach asks teams of six to spend five minutes developing three potential solutions on a piece of paper with a 6x3 grid on it. After five minutes, team members pass their paper to the left and receive one from the right and the five-minute brainstorming is repeated. This time, the team members are encouraged to examine existing solutions on the paper that was passed to them and use them as inspiration for their next three solutions. The process is repeated until all team members receive their original piece of paper with their ideas at the top of the grid. 6-3-5 enables more equitable idea sharing by providing each participant equal opportunity to submit ideas. We used the 6-3-5 technique in the present research.

Paradigm-Relatedness and Ideation

Another critical framework for understanding brainstorming output is paradigm-relatedness. The Paradigm-Relatedness Framework classifies ideas or design solutions as either paradigm preserving or paradigm modifying, depending on the extent to which they conform to or diverge from the traditional solution space, respectively [8]. This framework distinguishes between ideas that resemble or leverage existing solutions (or preserve the paradigm) and those that involve more drastic or fundamental changes to existing solutions (those that modify the paradigm). The framework helps to describe the degree to which brainstorming output might contain novel or innovative solutions. Rechkemmer et al. (2017) used this framework to examine the effects of task framing on paradigm preservation or modification [9]. They found that task framing can influence ideation styles and creative output.

Paradigm-relatedness can also be applied at the group level. Garfield and others (2001) used paradigm-relatedness to explore how the ideation style of an individual may influence the style of an entire group [10]. They found that greater exposure to paradigm-modifying ideas from an individual resulted in a greater number of paradigm-modifying ideas from the entire group. Relatedly, Dennis et al. (2012) found that individual exposure to creative stimuli via cognitive priming had a positive impact on the creativity of a group [2]. These findings provide insights into how various interventions can influence the creative styles of both an individual and a broader group.

Ideation Medium Preferences

Another important factor in brainstorming studies is ideation preferences—specifically, whether an individual prefers to brainstorm visually (sketching) or verbally, individual or collaboratively, etc. A case study by Jonson found that verbal idea generation, more than sketching, was the preferred medium to initiate a brainstorming exercise [11]. Individual preferences of the brainstorming medium are important because the easier it is to ideate, the more ideas an individual may be able to produce. Relatedly, Yang and Cham examined the role of sketching ideas in a design course and compared their initial drawings to their final output (a physical prototype) [12]. Results did not show a conclusive correlation between sketching skills during initial ideation and the final output. This is noteworthy because those with better sketching skills may be able to translate their thoughts to images more efficiently than others. Nevertheless, sketching often plays an important role in idea generation [13], [14].

Methods

The purpose of this research is to examine the challenges students experience as well as the recommendations they make for improving conceptual brainstorming activities. To do so, we recruited 36 mechanical engineering students in their second and third years to perform a conceptual design brainstorming exercise. Following the brainstorming session, we conducted retrospective focus groups where students reflected on their processes and offered insight into different suggestions to enhance brainstorming for future groups of students. The following sections describe the student sample, the data collection, and the thematic analysis approaches [15] used to develop our findings in terms of salient challenges and recommendations.

Student Sample

We recruited 36 second- and third-year students from a mechanical engineering department at a large, public, teaching-focused university in central California. We selected mechanical engineering for three key reasons: 1) the relative size of the department (approximately 1200 students); 2) the focus on creative product design and; 3) access to the student population through departmental listservs. First, the mechanical engineering department is the largest engineering department on campus, and so it offered the greatest potential to stratify student samples according to relevant demographic characteristics (e.g., [16], [17]). Second, mechanical engineering disciplines often deal with consumer products and systems and engage in creative ideation related to novel solutions to human-centered problems. Finally, the last author and PI on the project is a professor in the mechanical engineering department and thus had access to student listservs from which to recruit students. Selecting students in this way therefore represents a combination of both convenience and purposive sampling, as is common in qualitative research [18].

According to our screening survey, 17 of the participants used she/her/hers pronouns and 19 used he/him/his. Twenty-two participants identified as white, eight as Asian, five as Hispanic, and one as mixed race. Students were given a $25 Amazon gift card for their participation in the research. Student groups were varied in terms of gender composition and activity structure in order to examine potential effects of these variables across contexts (see [16], [17] for a fuller discussion of these studies). In total there were two groups that were predominantly male, two that were predominantly female, and two that were balanced in terms of gender.

Data Collection and Analysis
To complete the brainstorming activity, we used a prompt related to the development of new playground equipment consistent with previous research on ideation design processes [19]. Participant teams completed either a structured brainstorming session using the 6-3-5 method [7] or a more free-form activity in which participants could discuss ideas in any fashion they chose (i.e., unstructured).

Following the brainstorming session, we conducted retrospective focus groups with student teams. The protocol was semi-structured to allow for both consistency across groups as well as the ability to diverge and follow important but unanticipated threads of conversation. The protocol asked students to reflect on and describe a few aspects of their experience. First, we asked students to summarize their general process of brainstorming and their decision-making approaches. Next, we asked students to describe any challenges they encountered during the session in terms of communication, leadership, and other relevant aspects of the process. Next, we asked about specific solutions students developed and asked them to elaborate on the ways they developed those solutions and what ideas inspired them. Finally, we asked students to speculate on what they might do differently or change about their approach and to offer some recommendations to students who might be working on this problem in the future. Focus groups lasted approximately 45 minutes and all data were collected in compliance with the local IRB office. All focus groups were audio recorded and transcribed by a professional transcription service.

To analyze our focus group data, we followed recommendations by Saldana (2015), using both first- and second-cycle methods. For first cycle methods, we used procedures for initial coding, process coding, and descriptive coding. For the second cycle, we implemented pattern coding to facilitate organization of our findings in ways that would be useful for a broader audience of engineering educators and design researchers. This process involved developing initial codes based on emergent themes within the data, grouping those codes in terms of the relevant processes they described, and working recursively through the data to operationalize themes and supporting subcodes. For our final cycle, we developed criteria for inclusion within the codebook in order to capture all instances in which a code was encountered and to highlight specific examples within each theme. Additionally, we applied exclusion criteria to establish clearer boundaries between more abstract codes.

To achieve credibility and trustworthiness, we followed recommendations by Rossman & Rallis (2003), who offer different techniques for ensuring quality and consistency in qualitative analysis. Specifically, we performed independent review of the codes and transcripts in which Authors 3 and 4 independently reviewed sections of transcripts, assigned codes, and compared those assignments with those applied by Authors 1 and 2. In the case of disagreements, discrepancies were argued to consensus and the codebook and operational definitions were modified to reflect a new consensus. By performing this kind of reliability check, we were able to define the conceptual boundaries of codes and develop clear and consistent inclusion criteria for a focus group passage to be assigned a particular code.

Limitations
It is critical to interpret our research in light of existing limitations to our design. To conduct this study, we recruited engineering students from an undergraduate-focused institution in California. The sample size consisted of 36 participants (19 men and 17 women) comprising six brainstorming

groups. While our analysis is generally at the group level, another limitation is the fact that focus groups can overlook individual perspectives that might be present. At the same time, however, they also offer insight into group dynamics that might not have been able to be captured via individual interviews.

Additionally, our work focused on second- and third-year mechanical engineering students. We chose this group in order to manage the scope of the research and to limit the number of potential factors that might affect brainstorming outcomes. But we also chose this group to minimize disparities in design skills and familiarity with team-based environments. We did not stratify the brainstorming groups according to students' year in school and so data are not available regarding differences across second- and third-year participants. As suggested by Lai et al., creative capacity may correlate with class standing, so our results may not be representative of first year and/or graduating students [21].

Another limitation is that these students all come from the same major, and while we controlled for gender, most students were white. These perspectives might therefore represent a relatively narrow set of experiences of engineers. However, the demographics were still consistent with those of the broader college of engineering, and so findings could be relevant in similar contexts. That does not excuse the lack of diversity of the sample, and researchers should certainly work to include a broader range of student voices, but the student demographics in our samples are relatively representative of the college of engineering from which they were sampled. It is nonetheless important for future work to include broader voices and explore how different groups experience critical aspects of engineering learning.

Results

We present our findings in terms of the two major themes and their associated codes that serve to further define and operationalize our definitions. Table 1 summarizes these themes, which will be further elaborated in the following sections. (Though an analysis of the role of gender and activity structure is beyond the scope of the present work, see [16] for a fuller discussion). The focus group quotes are identified according to their structure and gender composition. US = Unstructured. S = Structured. PM = Predominantly Male. PF = Predominantly Female. B = Balanced.

Table 1: Overview of salient themes and associated codes.

Theme	Operational Definition	Associated Codes
Challenges	Difficulties and areas of stagnation or confusion encountered by students as they engage in brainstorming activities	• Ideation preferences and styles • Limited information of design context • Feasibility and improvised constraints
Recommendations	Suggestions for improving the overall process of brainstorming and idea generation related to developing solutions	• Communication and organization • Understanding tasks and market • Limit judgment and constraints

Challenges

Students in this study noted three dominant challenges associated with their brainstorming activity. These challenges highlight the importance of the idiosyncratic and sometimes personalized nature of brainstorming, design context, and students' inability to ignore common, often implicit, engineering constraints that are self-imposed onto problems. Table 2 provides an overview of these different salient challenges and the following sections provide some elaboration and support quotes from student focus groups.

Table 2: Overview of codes and subcodes related to challenges.

Salient Challenge	Operational Definition	Subcodes
Ideation Preferences and Styles	Differences in how individuals prefer to develop, share, and collaborate on ideas	• Ideation Medium • Individual vs. Collaborative • Planning and Organization • Building On Other Designs
Limited Information of Design Context	Restricted exposure to the design space, which results in a plateau of idea throughput	• Lack of familiarity • Running out of ideas
Feasibility and Improvised Constraints	Students' inability to ignore self-imposed constraints and the premature rejection of ideas	• Feasibility • Making Early Judgments • Influence of Education

Ideation Preferences and Styles

While brainstorming, students encountered issues related to individual members' *Ideation Preferences and Styles* which addresses the personalized and idiosyncratic nature of the way different students prefer to engage in creative ideation activities. There were various aspects that students had preference over, including the means of how they communicated their ideas to one another. *Medium (sketching vs writing vs verbal)* describes challenges associated with the tools for communication available in a given ideation session. For example, certain individuals preferred having visual aids rather than written down ideas when sharing with others. At the same time, other members believe that with limited visual resources, words can beneficially impact design.

> *Female 2: A picture's worth 1000 words to an extent just because we have artistic ability kind of dragging us down right now (US/PF).*

While this student highlights the significance of having visual aids, they recognize that hand drawings can be more difficult to communicate and interpret. In particular, students expressed explicit preferences for either visual or verbal ideation—with preferences often differing within groups. This may limit throughput and collaboration if students struggle to effectively communicate and understand others' ideas.

Additionally, *Building off Other Designs* addresses issues students had working with and making sense of what others have done and using prior ideas to generate new/modified ones. As ideation progressed, groups used existing ideas to inspire newer ones.

> *Female 2: At the beginning, I was just thinking about playgrounds in my childhood and thinking what did I like to do or what did I see other kids doing and how could that be*

> *accessible for everybody? And then as we went along just reading other people's ideas, that would often spark other thoughts and trying to improve upon those or I'd complete up with something completely new just based off of inspiration from those (S/PM).*

Other challenges seemed to arise based upon team structure as students have certain preferences between working in a team or individually. *Individual vs Collaborative* refers to challenges associated with the social aspects of students' preferences. Some students preferred to brainstorm alone and then share, while others enjoyed the dynamic process of group ideation.

> *Female 1: I feel like I would've sketched by myself and then seen what everyone else did, instead of kind of, just speaking about it. Some of us writing it down, some of us not. But kind of generating your ideas on your own and having that space for yourself, instead of having to speak up in front of a group is sometimes hard for people (US/PM).*

While structured groups brainstormed silently, unstructured groups were able to freely discuss ideas verbally throughout the entire process. The freedom to talk limited unstructured groups' ability to ideate without the influence of other members. For example, students struggled to develop their own ideas when the group was discussing something else. Moreover, this can create challenges for members who may not be able to express their ideas equally.

Participants also seemed to be challenged by the organization of the sessions. *Planning and Organization* captures challenges with how to structure and sequence the activity. For example, the following excerpt illustrates how students experienced challenges related to delegation of tasks and keeping track of their ideas.

> *Male 1: We didn't really have delegated roles, we just kind of just started spitting ideas. No one wrote anything down. So in the beginning, people were talking about their own ideas, towards the end, I started to forget what we talked about in the beginning. So maybe if we had a chart of, 'Oh what did we do?' and what ideas we covered. It could be like, 'Oh, I want to talk about that one.' That's why I like the whiteboard.*
> *Female 1: It wasn't well-documented (US/PF).*

While they were able to talk about ideas, these groups did not write down key design ideas as the session progressed.

Limited Information of Design Context

Limited Information of Design Context focuses on the challenges groups face associated with their lack of knowledge of the design prompt and is defined in terms of two subcodes. *Lack of Familiarity* discusses how there was limited exposure and insight to stakeholders within the design space. This limited the students' ideation as they were having difficulty being personable with the market. For example, one student noted

> *Male 3: To summarize, well, I think we're just really far removed from the customer because we can't really relate to them (S/B).*

These instances reflect how limited exposure to the design space can pose a challenge to ideation.

Additionally*, Running out of ideas* describes about instances where participants exhausted all options and/or became mentally fatigued. Students seemed to come to roadblocks during ideation, especially in the structured groups with limited verbal communication.

> *Female 2: Just trying to think of new unique ideas. Sometimes it feels just like you've got a mental block where you're looking at a blank page and I'd don't what to think about (S/PM).*

Limited information may confine the scope of the design space, which makes it easier to run out of potential solutions.

Feasibility and Improvised Constraints

Other factors negatively impacted ideation, including students not being able to remove barriers to creative ideation. *Feasibility and Improvised Constraints* refers to challenges students had related to their inability to remove fictitious constraints that limit ideation. For example, *Feasibility* captures students' reticence to ignore design constraints such as safety, manufacturability, etc. While the prompt stated there are no constraints, and even asked students to do their best to ignore them, they still seemed challenged with feasibility as they formed implicit criteria that limited idea generation.

> *Female 1: I personally like having problem constraints, because then I know what I can do. I know what my space is that I can work in. So, I honestly think for most of us, I hope, like we were doing the first three rows, it seems, and we're just like, well, this is a constraint like cost or like accessibility, or actually, feasibility. And then, later on, it's like, actually, they said that we didn't really need that. So, I'm just going to do some abstract stuff (S/B).*

In addition, *Making Early Judgements or Evaluations* were instances when team members decided too soon if an idea is good or bad, or by attempting to preserve the paradigm by suppressing 'radical' ideas.

> *Male 2: I was trying to get maybe a circular thing like that going, but I just didn't know how that would work so I just didn't draw it, but it could have been a drawing.*
> *Male 3: I also thought of that idea, but then I couldn't figure out how to make it work so then I didn't draw it or anything (S/PM).*

Students seemed to evaluate their own ideas prior to sharing them with other members. If students felt ideas were not "good enough," they omitted them from their brainstorm. Moreover, students felt that their background in engineering curriculum led them to make certain design decisions. *Influence of Education* therefore describes the self-imposed constraints ingrained from engineering education which was often used to justify why they failed to ignore constraints.

> *Female 2: I think in the first like three parts. You go around and you realize like, we're all a lot of MEs or a lot of engineers that were pulled and so our thought process, our brains for creativity often is quite similar. So, when we all have merry-go-round, and this and that. You realize you're like, 'Well, I thought I'm a creative person.' But when I have people around me that are so similar often like, we produce the same starting point (S/B).*

This example demonstrates how the engineering courses have hindered their ability to ideate progressively. These constraints caused students to make preliminary considerations that restricted the ideas they expressed as they omitted certain ideas based upon their own criteria.

Taken together, our findings illustrate a range of challenges identified by students that they perceive to interfere with effective ideation activities. Differing ideation preferences and styles made it difficult for students to follow a set structure, whether it be 6-3-5 or verbal brainstorming. Students' limited exposure to the design context also made it difficult to factor in user needs and may have made them more prone to running out of ideas. In addition, students seemed to struggle with limitations pertaining to feasibility and self-imposed constraints that hindered their creative ability. While these emergent themes were highlighted by the focus groups, students were able to offer recommendations that can ultimately enhance ideation.

Student Recommendations

Students also offered recommendations for ways to improve upon their process and gave some advice for students working on similar tasks in the future. In particular, students articulated recommendations around three emergent categories: *Understanding Tasks and Market*, *Limit Judgement and Constraints*, and *Communication and Organization* within the group. Table 3 provides an overview of these recommendations and the following sections provide elaboration and support quotes from student focus groups. An important note about this particular theme is that these findings are not necessarily recommendations that the authors would make or actions that we believe faculty should take. Rather, they represent dominant themes in student responses to questions about how they would change their process in the future or recommendations they would offer to future students engaging in a similar task. In an effort to avoid conflating findings with implications, we make more specific, actionable recommendations in the Discussion and Implications section below.

Table 3: Overview of codes and subcodes related to student recommendations.

Student Recommendation	**Operational Definition**	**Subcodes**
Communication and Organization	Enhancing the method, process, and format of group interactions	• Planning and Organization • Communication • Individual and Collaborative Time
Understanding Tasks and Market	Clarifying a student's understanding of the ideation topic and the needs of end users	• Engagement with Stakeholder(s) • Clarify the Task
Limit Judgment and Constraints	Encouraging an ideation environment free from brainstorming constraints and open to paradigm-modification	• Ignore Constraints • Modify the Paradigm

Communication and Organization

Based on differing ideation preferences, *Communication and Organization* highlights students wanting more effective group management strategies in order to enhance facilitation and ideation. Since this session was conducted under a time constraint, students wanted to implement more efficient techniques that can positively impact their ideas. *Planning and Organization* discusses making use of better structural methods for time efficiency and formatting the ideation process more effectively.

> *Female 1: Just a thought. I don't know how this would change the thought experiment if you gave us each like three squares. Right? Then before we moved on to our partner, we picked our favorite and you kept the rest and they gave us each three more blank squares. So you're only seeing one instead of three ideas (S/PF).*

Structured groups recommend varying the structured format in order to allow for focus on the more prominent ideas generated by their group members.

Communication recommendations highlight the importance of productive interpersonal interactions on a team. Being able to effectively communicate within the team helps clarify any misunderstanding and gives everyone the opportunity to be engaged.

> *Female 2: It was just the one method of the brainstorming process. Other methods would be talking to people, writing stuff on the board and more interactive and more verbal. But this is a really good way of getting ideas started. That's not the only way of brainstorming (S/PM).*

While these groups seemed to enjoy individual ideation, students also noted the importance of verbal communication to ensure all members are on the same page. The emphasis on regulating time efficiently during the brainstorming sessions was prominent as students discussed wanting differing perspectives and means of collaboration.

Individual and collaborative time refers to students grappling with the balance of group and solitary ideation processes and recognizing the differences in student preferences.

> *Male 2: I think it would be good to give everyone like five minutes at the start, to just brainstorm on their own and come up with what they think would be a good idea, and then go around and share those ideas.*
> *Faciliator: How come?*
> *Male 2: I think because at the beginning when one person throws out something, then everyone starts to think about that and you just keep building off of that thing instead of making your own ideas. And then, some people might have the same ideas so you can work together on those. (U/PM)*

Students preferred a balance of both modes of ideation would foster better ideas since members get the opportunity to work with each other while also generating their own solutions to the design prompt.

Understanding Tasks and Market

Understanding Tasks and Market addresses the perceived importance of knowledge of stakeholders who might use or interact with the design. The first code, *Engagement with Stakeholder,* emphasizes specific instances where students suggest interaction with actual users of the design.

Female 1: I have like two things, but they're kind of separate. But the first one, regarding doing it over, I feel like maybe even just having a wheelchair here while we were doing it. Yeah, we don't have the same experience or maybe even bringing someone in, but being to see what you can and cannot do physically, because we all have an idea of what it is, but we don't actually know what it is. Have you actually ever been in one? And so being able to have that as our, I guess it's kind of a limiting factor, but it's important to know what your guidelines are (US/PM).

Students recommended gaining additional knowledge of stakeholders and their needs for better design ideation.

Aside from the design space, students had issues analyzing certain aspects of the prompt. *Clarifying the task* refers to when students noted a desire for more elaborate or detailed instructions regarding the prompt.

Female 1: Maybe a way to pose the question would be like you're constructing new or modified pieces of playground equipment for children who are indestructible. And then we be like, oh, well, they're indestructible. They can go through metal and they can fall down as much as they want you know... like an unstoppable... what is it, an unstoppable force meets an immovable object? A child and a playground equipment (US/B).

Students had difficulty clearly interpreting the prompt and expressed the benefits of modifying or clarifying the prompt in ways that might stimulate better ideation.

Limit Judgement and Constraints

Students also made recommendations pertaining to feasibility challenges associated with the brainstorming session. *Limit Judgement and Constraints* describes student recommendations to improve creativity by removing limitations that negatively impacted their design solutions. The first code for the theme is *Ignore Constraints* which refer to comments regarding the importance of eliminating false or self-imposed constraints that might interfere with conceptual and preliminary brainstorming processes.

Male 1: Really emphasize immediately that you have no constraints and try to get that through to them so they don't started after the same thing, trying to do something feasible.
Male 2: I'm kind of curious about what the results would have been if we had, I don't know, if somebody had been like, 'Remember infinite budget, no constraints. Remember that,' like hammered that into us? I kind of feel like we would have gotten like way more abstract concepts (S/B).

Although it was explicitly stated, students wanted constant reminders to cement the idea to think freely without considering restricting factors. By ignoring constraints, students believed they were able to generate more innovative ideas. Students also discussed how the design prompt hinted towards creating ideas that are similar to traditional playgrounds. *Modifying the Paradigm* was defined as actions or thoughts used to shift from paradigm-preserving to paradigm-modifying ideation. In particular, strategies used to generate more "radical" ideas that deviate from the norm (e.g., traditional playground equipment).

Male 2: I don't know if this is something I would tell someone but like, maybe some kind of emphasis on... I don't know, I don't want to limit ideas, but I definitely think some kind of emphasis on you don't just have to adapt an able-bodied piece of equipment. It says it in the prompts, that you can also just invent something, but yeah (S/B).

Students recommend exploring ideas beyond stereotypical designs within narrow (or potentially fictitious) requirements. By taking steps to reimagine their designs at more fundamental levels (i.e., modifying the paradigm), students can be more creative and generate ideas that are substantially different from existing solutions.

In summation, students noted a range of challenges pertaining to team structure and implicit effects that the means of ideation offer. Despite these challenges, students found ways to mitigate and work through barriers in order to maximize idea output and creativity.

Discussion and Implications

Our findings highlight a range of challenges to effective ideation and recommendations to improve those processes and enhance student teams' creative output (and potentially quality of ideas). Our findings therefore point to three key areas in which engineering educators might focus in order to facilitate more effective ideation processes.

First, providing students with environments in which they can feel comfortable interacting and sharing with others appears vital to an effective brainstorming session. Student perspectives highlight the need for clear communication and support to ensure active engagement and idea sharing. Findings suggest that brainstorming preferences can be highly individual and idiosyncratic. Some noted a preference toward individual ideation, others a group, and some wanted a combination of both. Findings related to *Ideation Preferences* and *Communication and Organization* highlight the ways students might differ in their comfort level in particular kinds of brainstorming activities. Tending to these preferences (e.g., individual vs. collaborative, linear vs. sporadic, verbal vs. visual) is important because they will influence the ways students communicate or engage with a group engaged in brainstorming.

We recommend that engineering educators work to better understand student preferences and develop approaches that accommodate the full range of them. For example, faculty could form groups based on some of the ideation preferences noted by students in the recommendations section of our findings. By offering a wide range of ways for students to interact, instructors can encourage diverse forms of engagement and involvement of all students in a team. Instructors could use both structured and unstructured ideation formats to capture the benefits of each. One may start with structured ideation to give every participant equal opportunity to develop and submit ideas, then pivot to unstructured ideation for more collaborative iteration. Further, faculty might offer some guidance in terms of how to navigate salient challenges that occur during brainstorming activities. Specifically, instructors can normalize certain kinds of struggle (e.g., inability to ignore constraints) and discuss strategies related growth mindsets (e.g., [22]) as a means for overcoming some of these salient challenges. Doing so can help to promote equity in the way ideas are shared and communicated and can help all students more fully engage with their groups in meaningful ways.

Second, helping students grapple with rich design contexts and engage with authentic stakeholders and users might benefit ideation. Understanding the full design context might help students more effectively explore the design space (i.e., the set of possible solutions) and develop more novel or innovative ideas. Students reported a range of challenges, but one particularly dominant area concerned students feeling like they had insufficient knowledge about users or other relevant stakeholders in the design context. For our findings, the inability to speak with someone who might use their design (e.g., a child in a wheelchair) hindered their ability to develop effective solutions. Human-Centered Design processes describe the importance of empathy and understanding human experiences in problem definition, and our findings point to the importance of that empathy in conducting brainstorming as well [23]. Based upon these findings, we suggest engineering educators work to provide students with authentic design contexts and stakeholders to meaningfully interact with. Doing so might help students cultivate the empathy needed to better understand design problems and more fully explore novel solutions.

Third, it seems important to address how participants in this study sometimes struggled to remove constraints and think in divergent ways that might have led to more novel solutions. Codes such as *Improvised Constraints* and the recommendation to include more frequent reminders of the need to limit judgment highlight the ways students often struggled to "get out of their own way" when it came to developing novel ideas. Researchers have described this as "design fixation," which indicates an inability to reimagine systems or solutions in ways that do not leverage existing solutions [24], [25].

Finally, it is particularly disconcerting to hear students cite the *Influence of Education* as a contributor to this fixation and inability to think more creatively. Researchers have observed this effect in which senior engineering students score lower on measures of creativity than their first-year counterparts (e.g., Sola, Hoekstra, Fiore, & McCauley (2017), and students in this study seem to call explicit attention to this issue. Future research should certainly investigate the reasons an engineering curriculum might hinder creativity over time, but providing students with more opportunities to express their creativity seems a useful place to start. Instructors could accomplish this through more open-ended problems or "wicked" problems, which have many solutions that all involve trade-offs and compromises. Such problems might help students think more creatively about engineering solutions in ways that help them grow in their creative capacity over time. Additionally, problem framing tools designed to shift ideation towards paradigm-modification (e.g., Rechkemmer et al. (2017)) may help students ignore constraints and think more creatively.

Future Work

Within the field of engineering education, the *Influence of Education* on students' capacity to ideate is particularly worthy of further investigation. Specifically, how engineering courses may limit a student's ability to ideate. This is supported by Lai et al.'s (2008) findings that suggest an inverse relationship between the number of years in engineering courses and one's ability to do divergent thinking. Researchers may consider the role of design and creativity courses in engineering education, such as the Ideation Laboratory at MIT [27]. Further, researchers might explore the influence of innovation-oriented liberal arts or business classes (e.g., product design, entrepreneurship, etc.) on engineers' ability to think creatively. Such experiences could expose students to different domains of ideation while providing an opportunity to collaborate with non-engineers. Further, being comfortable seems conducive to open ideation and helps participants more freely share ideas and take the time to understand others. However, as shown in our study, individual preferences within a group tend to be conflicting. This may support nominal over group ideation (e.g., [4], [5]), or more silent and independent group methods, such as 6-3-5. Researchers may consider if, how, and when individual ideation preferences should be accommodated, particularly within a group setting.

Conclusion

Brainstorming plays a pivotal role within engineering education and this study highlights the importance of offering diverse opportunities in ways that help students generate expansive ideas. Moreover, this study helped illuminate challenges within brainstorming groups and offer student perspectives that allow for valuable insights and experiences. Students were able to identify aspects that can be better suited for idea generation and suggest recommendations that might lead to more effective brainstorming practices and therefore a fuller exploration of the design space.

Based on the themes identified, we found students want to be in a comfortable environment that promotes the free sharing of ideas. Their individual preferences played a major role capturing varying comfort levels with certain brainstorming formats. In order to help promote equity within the group, we suggest educators work to develop approaches to accommodate students in ways that address the full range of their personal and group-based preferences. Another major finding was students wanting more insight regarding the design context and engagement with stakeholders to better understand the needs of the end users. In order to mitigate this issue, we suggest that engineering educators give students more interaction with real stakeholders and authentic design contexts. Lastly, we found that students struggled with removing constraints in ways that interfered with their ability to generate novel ideas; these constraints were noted as being a result of a specific kind of engineering education and way of thinking. Consequently, we recommend instructors should work to incorporate more open-ended problems which have vast solutions that can enhance students' creative capacity. Integrating student voices into the conversation surrounding ideation and creativity during brainstorming offers useful perspectives for identifying and thus responding to significant challenges. Such responses may not only improve students' experiences but enhance the overall creative output of brainstorming activities.

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References

[1] R. B. Gallupe and W. H. Cooper, "Brainstorming electronically," *MIT Sloan Manag. Rev.*, vol. 35, no. 1, p. 27, 1993.
[2] A. R. Dennis, R. K. Minas, and A. P. Bhagwatwar, "Sparking creativity: Improving electronic brainstorming with individual cognitive priming," *J. Manag. Inf. Syst.*, vol. 29, no. 4, pp. 195–216, 2013.
[3] A. F. Osborn, "Applied imagination.," 1953.
[4] T. J. Bouchard Jr and M. Hare, "Size, performance, and potential in brainstorming groups.," *J. Appl. Psychol.*, vol. 54, no. 1p1, p. 51, 1970.
[5] R. B. Gallupe, L. M. Bastianutti, and W. H. Cooper, "Unblocking brainstorms.," *J. Appl. Psychol.*, vol. 76,

no. 1, p. 137, 1991.
[6] W. H. Cooper, R. B. Gallupe, S. Pollard, and J. Cadsby, “Some liberating effects of anonymous electronic brainstorming,” *Small Gr. Res.*, vol. 29, no. 2, pp. 147–178, 1998.
[7] M. Litcanu, O. Prostean, C. Oros, and A. V. Mnerie, “Brain-writing vs. Brainstorming case study for power engineering education,” *Procedia-Social Behav. Sci.*, vol. 191, pp. 387–390, 2015.
[8] L. D. Douglas, M. H. Jillian, L. R. Thomas, and L. S. Eric, “Identifying quality, novel, and creative ideas: constructs and scales for idea evaluation1,” *J. Assoc. Inf. Syst.*, vol. 7, no. 10, p. 646, 2006.
[9] A. E. Rechkemmer *et al.*, “Examining the effect of a paradigm-relatedness problem-framing tool on idea generation,” in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2017, vol. 2017.
[10] M. J. Garfield, N. J. Taylor, A. R. Dennis, and J. W. Satzinger, “Modifying paradigms—Individual differences, creativity techniques, and exposure to ideas in group idea generation,” *Inf. Syst. Res.*, vol. 12, no. 3, pp. 322–333, 2001.
[11] B. Jonson, “Design ideation: the conceptual sketch in the digital age,” *Des. Stud.*, vol. 26, no. 6, pp. 613–624, 2005.
[12] M. C. Yang and J. G. Cham, “An analysis of sketching skill and its role in early stage engineering design,” 2007.
[13] D. G. Ullman, S. Wood, and D. Craig, “The importance of drawing in the mechanical design process,” *Comput. Graph.*, vol. 14, no. 2, pp. 263–274, 1990.
[14] V. Goel, *Sketches of thought*. MIt Press, 1995.
[15] V. Braun and V. Clarke, “Using thematic analysis in psychology,” *Qual. Res. Psychol.*, vol. 3, no. 2, pp. 77–101, 2006.
[16] G. Gius, A. Osman, M. Nevrly, and B. D. Lutz, “Exploring the Influence of Team Gender Composition During Conceptual Brainstorming,” in *American Society for Engineering Education Annual Conference Pacific Southwest Division*, 2020.
[17] M. E. Cuellar, D. Trageser, R. Cruz-Lozano, and B. D. Lutz, “Exploring the Influence of Gender Composition and Activity Structure on Engineering Teams’ Ideation Effectiveness,” in *American Society for Engineering Education Annual Conference*, 2020.
[18] M. Q. Patton, “Sampling, qualitative (purposive),” *Blackwell Encycl. Sociol.*, 2007.
[19] C. J. Atman, R. S. Adams, M. E. Cardella, J. Turns, S. Mosberg, and J. Saleem, “Engineering Design Processes: A Comparison of Students and Expert Practitioners,” *J. Eng. Educ.*, vol. 96, no. 4, pp. 359–379, 2007.
[20] G. B. Rossman and S. F. Rallis, *Learning in the field: An introduction to qualitative research*. Sage, 2003.
[21] J. Y. Lai, E. T. Roan, H. C. Greenberg, and M. C. Yang, “Prompt versus problem: Helping students learn to frame problems and think creatively,” in *Proceedings of the 2nd Design Creativity Workshop, Third International Conference on Design Computing and Cognition*, 2008, pp. 1–6.
[22] C. S. Dweck, *Mindset: The new psychology of success*. Random House Digital, Inc., 2008.
[23] C. B. Zoltowski, W. C. Oakes, and M. E. Cardella, “Students’ ways of experiencing human-centered design,” *J. Eng. Educ.*, vol. 101, no. 1, pp. 28–59, 2012.
[24] R. J. Youmans, “The effects of physical prototyping and group work on the reduction of design fixation,” *Des. Stud.*, vol. 32, no. 2, pp. 115–138, 2011.
[25] D. G. Jansson and S. M. Smith, “Design fixation,” *Des. Stud.*, vol. 12, no. 1, pp. 3–11, 1991.
[26] E. Sola, R. Hoekstra, S. Fiore, and P. McCauley, “An investigation of the state of creativity and critical thinking in engineering undergraduates,” *Creat. Educ.*, vol. 8, no. 09, p. 1495, 2017.
[27] “MIT Ideation Laboratory.” .