Daniel Henderson
Department of Engineering Science and Mechanics,
The Pennsylvania State University,
University Park, PA 16802

Kathryn Jablokow
School of Graduate Professional Studies,
The Pennsylvania State University,
Malvern, PA 19355

Shanna Daly
Department of Mechanical Engineering,
University of Michigan,
Ann Arbor, MI 48109

Seda McKilligan
Department of Industrial Design,
Iowa State University,
Ames, IA 50011

Eli Silk
Graduate School of Education,
Rutgers University,
New Brunswick, NJ 08901

Jennifer Bracken
Department of Mechanical and
Nuclear Engineering,
The Pennsylvania State University,
University Park, PA 16802

Comparing the Effects of Design Interventions on the Quality of Design Concepts as a Reflection of Ideation Flexibility

Many tools, techniques, and other interventions have been developed to support idea generation within the design process. In previous research, we explored the separate effects of three such design interventions: teaming, problem framing, and design heuristics. In the teaming intervention, participants discussed a design prompt together but recorded their own ideas separately. In problem framing, multiple versions (framings) of each design prompt were used to elicit different solutions. In design heuristics, participants used specially designed cards to prompt new ways of thinking about the given design problem. In the current work, we compared the effects of these three interventions on students' design ideas with respect to one idea attribute in particular—quality. In total, 1088 design concepts were collected from 171 undergraduate students in engineering and industrial design from two universities. Individual cognitive style was also assessed using Kirton's Adaption–Innovation inventory (KAI). Six metrics taken from the design literature were used to assess the quality of each concept, namely: acceptability, applicability, clarity, effectiveness, implementability, and implicational explicitness. Paired t-tests and Pearson correlations were used to assess differences in quality between concepts generated with and without the three interventions; in addition, secondary effects were sought based on the cognitive styles and academic standings of the participants. Statistically significant differences were observed in design concept quality for the teaming and design heuristics interventions over the full sample and for some subgroups separated by cognitive style and academic standing. These results have implications for how educators teach design interventions and how students choose and apply interventions to affect the quality of their own design solutions. [DOI: 10.1115/1.4042048]

Keywords: idea generation, design concepts, design interventions, quality metrics

Introduction

Idea generation or "ideation" is a critical skill for all engineers as they explore problem spaces and develop solutions [1,2]. One key success factor in ideation is "ideation flexibility"—i.e., an engineer's ability to move between his or her preferred and non-preferred ways of generating ideas as required by the current problem and/or the customer [3,4]. Unfortunately, engineering students are rarely (if ever) taught how to achieve this kind of flexibility. Design interventions have the potential to improve the idea generation performance and flexibility of engineers. Improving the ideation of engineers will ultimately lead to better design outcomes, which could result in more affordable, sustainable, and contextually appropriate solutions to emerging problems.

One form of ideation flexibility is the ability to generate both radical and incremental ideas, depending on the needs of the problem. We have previously assessed the radical versus incremental nature of design ideas via a paradigm-relatedness metric [5,6]. While paradigm-relatedness represents one important outcome measure, there are many ways design concepts can be assessed [1], including novelty, creativity, variety, elaboration, and practicality. The current study aimed to assess the *quality* of students' design ideas based on the application of three specific design interventions (cognitive style-based teaming, problem framing, and design heuristics [2–4]) and the use of six established quality metrics: acceptability, applicability, clarity, effectiveness, implementability, and implicational explicitness [7]. As a variety of design interventions and idea metrics exist, design scholarship will benefit from this focused look at specific interventions and metrics to facilitate design educators' and practitioners' choices of tools to support their problem-solving processes.

Ideation, Creativity, and Cognitive Style

Ideation is an important part of the design process that involves both formulating the problem to solve and generating ways to solve it. A popular model of this relationship was developed by Maher and Poon [8], who described the co-evolution of a problem space (i.e., the formulation and refinement of the problem) and a solution space (i.e., the set of design ideas generated to address the problem). These spaces are dynamic and evolve together over time. Information is exchanged between the spaces as the design process progresses, leading to both a better understanding of the problem and more appropriate solutions to that problem [9,10]. As an engineer's solution space expands, he/she has greater potential for finding a solution that satisfies the current design problem's constraints. If he/she does not fully explore the design space, however, the pool of possible solutions to explore later in the design process may not ultimately hold an appropriate solution [11,12]. In addition, having fewer ideas in the early stages of the design process has been linked to design fixation [13,14].

Cognitive style is defined as an individual's stable, characteristic cognitive preference for processing information, solving problems, making decisions, and generating ideas [15–21]. A well-established model of cognitive style is Kirton's

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Adaption–Innovation (A–I) theory [16], which states that (in the context of design ideation) cognitive style reflects the amount of structure a designer prefers as he/she generates ideas [15]. Those who prefer more structure in their ideation are considered "more adaptive," whereas those who tend to shed structure in ideation are considered "more innovative." [16]. More adaptive thinkers tend to offer incremental design ideas that follow existing paradigms and problem definitions through "tried and true" methods of improving or modifying preexisting solutions. As they generate ideas, they remain cognizant of the given constraints of a design problem and work within those boundaries. More innovative thinkers, on the other hand, prefer to generate more radical ideas that may challenge problem definitions and break paradigms [16,22–24]. Neither adaptive nor innovative ideas are inherently better in general, but different styles of thinking are likely to be more or less effective for different problems and circumstances [25].

As formally defined in the literature, cognitive style is independent of *cognitive level*—i.e., one's *ability* to generate solutions to problems (including design problems) as reflected by one's knowledge, experience, and/or skills [15,23,26–28]. Cognitive level relates to measures of intelligence (e.g., IQ score), capability (e.g., relevant experience), and performance (e.g., grade point average). So, whereas cognitive style indicates how one cognitively *prefers* to approach design, cognitive level indicates how well-equipped one is to successfully address design problems [15]. Research to support the independence of cognitive level and cognitive style is plentiful, including the works of Kirton and de Ciantis [29], Goldsmith [30], Hammerschmidt and Jennings [31], and Buttner et al. [32].

Additionally, because cognitive style is a cognitive *preference*, people can be motivated to ideate in ways counter to their cognitive style given sufficient reason; we refer to this ability as "ideation flexibility" [4]. More generally, it is an example of coping behavior [16], which enables an individual to behave in ways that do not align with their cognitive style when the need arises and sufficient motivation is present. The immediate value for an adaptive thinker to generate ideas in an innovative way or vice versa is to expand their available solution space [11]. This expanded solution space offers more opportunity to find the "right" solution [9,12]. Coping behavior in design ideation can be facilitated by design interventions [15,16] that support a more flexible ideation process, leading to more diverse solutions. We represent this relationship in Fig. 1 and discuss three specific interventions (*cognitive-style based teaming, problem framing,* and *design heuristics*) in their corresponding sections later. Under the influence of these (or other) interventions, ideation flexibility is reflected in and can be assessed through the changes observed in specific ideation metrics. In prior work, we focused on paradigm-relatedness to characterize the types of ideas generated with and without these three interventions [5,33]. However, we do not know the extent to which these same interventions impact other idea attributes; thus, in this work, we focus on the impact of these three ideation flexibility interventions on idea *quality*.

Cognitive Style in the Engineering Classroom. While the effects of cognitive style differences have been investigated across occupational contexts (e.g., education, industry, military) and disciplines (e.g., business, nursing, education, engineering)—as discussed in detail in Ref. [16]—very few studies have examined the specific relationship between cognitive style and academic major or standing. For example, while Jablokow et al.'s study of undergraduate engineering teams [34] reported on the cognitive style distribution of that sample, the students were not separated by major or academic standing as part of the analysis. Likewise, Rechkemmer et al. [5] examined the cognitive styles of pre-engineering students working with design tasks, but intended academic major was not considered. Jablokow et al.'s study of sophomore mechanical engineering students included an analysis of their cognitive style distribution [35], but the homogeneity of the sample provides no insight into potential academically linked differences. To our knowledge, Jablokow's study of graduate engineering students, which showed wide ranges of Kirton's Adaption–Innovation (KAI) scores among systems engineers, software engineers, and information scientists [23,36], is the only study to make an explicit link between cognitive style and engineering major; interestingly, those results confirmed Kirton's hypothesis [16] that the KAI means of occupational groups tend to align with the mode style of the problems typically addressed by their practitioners.

Cognitive Style-Based Teaming. In the study of design teams and their dynamics, many different approaches have been used in their construction and optimization [37–40]. Cognitive style-based teaming involves students working in groups (typically dyads) to generate ideas for a given design problem [4]. Each dyad consists of two students with distinct cognitive styles and preferred ideation approaches. As an intervention, the goal of cognitive style-based teaming is to help both members of the dyad generate ideas they would not normally create through the influence of interacting with their teammate. Depending on the degree of difference between the partners' cognitive styles, dyads may experience teamwork very differently [16]. Perhaps the team members have very similar cognitive styles, so they approach ideation in similar ways and collaborate easily, but they do not generate ideas that lie beyond their shared way of thinking. On the other hand, a team may consist of two people with very different cognitive styles, so they approach ideation differently and generate diverse ideas, but they must also resolve their cognitive differences as they work together. Some research suggests that heterogeneous teams with less expertise can outperform

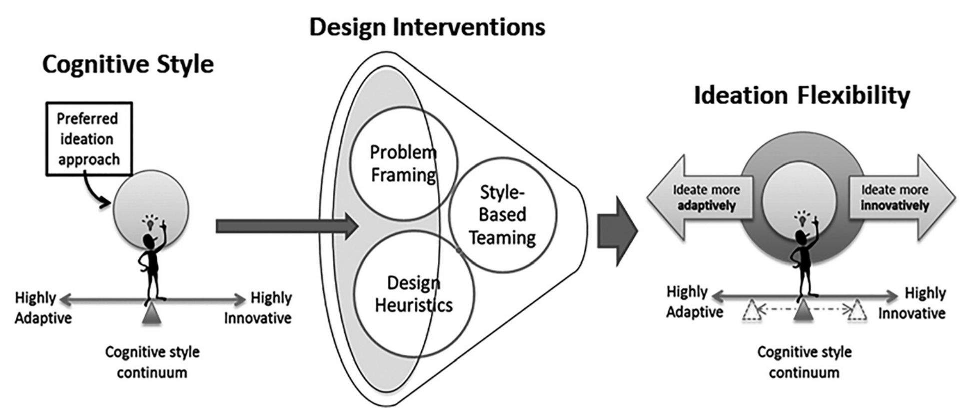


Fig. 1 Visual summary of the ideation flexibility project. Adapted from [4].

homogeneous teams with greater expertise because of their greater cognitive diversity [41,42]. However, if a team that is homogeneous in cognitive style is able to generate diverse ideas through their use of ideation flexibility, despite their preference toward one type of ideation, they may perform more effectively as a team.

Problem Framing. In addition to teaming, the way in which problems are presented, or framed, can influence ideation outcomes [43]. If a problem statement includes biased phrases that strongly reflect only adaptive or innovative thinking, for example, designers may be swayed to ideate in different ways than their preferred ideation approach as a result [16]. We created the design problem framework (DPF) as a problem framing tool to explore this phenomenon. The DPF takes a given design problem and restates it in both more adaptive and more innovative ways to stimulate different types of design ideas [3] (see Fig. 2). A neutrally framed problem statement provides only the basic context, need, and goal for a design problem without providing specific criteria or constraints that may bias a designer toward incremental (more adaptive) or radical (more innovative) ideas [3]. As a designer reads a neutral prompt, he or she does not feel "pushed" to ideate in any particular way; consequently, he/she is likely to generate solutions consistent with his/her preferred ideation approach [16]. Ideas generated using neutrally framed design problems provide the benchmark results for that designer.

Guided by A–I theory and the understanding that adaptive thinkers prefer more structure, whereas innovative thinkers prefer less structure [16], adaptively framing a design problem encourages incremental design ideas by introducing constraints and criteria that provide greater structure in the design problem statement. An innovative framing, on the other hand, encourages radical idea generation by introducing criteria and constraints (or freedoms) that reduce the structure of the design problem statement. All of the text *not* underlined in Fig. 2 is the neutral version of the given design problem; the underlined text is added to frame the problem. Phrases like "focus on improving existing designs" and "cost-effective and immediately workable" are examples of criteria and constraints to encourage designers to generate ideas in an adaptive manner [3]. In contrast, phrases like "focus on creating totally new designs" and "without concern for cost or immediate workability" are examples of criteria and constraints to encourage innovative thinking [3].

In developing the DPF, validation experiments were conducted to determine the extent to which the adaptive and innovative framings would change (or not) the types of solutions participants generated [3,6]. The results of these experiments indicate that the more explicit the framing, the more likely students will generate ideas of the type prompted by the problem [5,6]. In fact, when students applied the problem criteria themselves, they made the largest shifts in the paradigm-relatedness of their ideas [5]. However, the impact of the problem framing on other idea attributes, such as elaboration and quality, has not been explored.

Additionally, the design problems used in our studies were either adapted from research or newly developed during the creation of the DPF, as described in Ref. [3]. These problems were tested to see how they compared with respect to the diversity of ideas generated in each case; design prompts that led to low diversity of generated ideas were excluded (see details of all design prompts in Ref. [44]). As a key goal is to measure shifts in ideation, problems that already lead to low diversity of ideas would make the shifts in ideation more difficult to measure.

Design Heuristics. In addition to teaming and problem framing, ideation tools can be provided to help encourage flexibility in ideation, both individually and in groups [45–47]. One such tool is the *77 Cards: Design Heuristics for Inspiring Ideas* (also called "DH cards") [2,12,48,49]. Each card cites a short design heuristic, an explanation of that heuristic, and an abstract example on the front of the card. The reverse side has two concrete examples of the design heuristic as applied to products. On every DH card, one of these two concrete examples is a seating structure, which provides some consistency between heuristics. The 76th card, "utilize opposite surface," is shown in Fig. 3 as an example.

The DH cards were developed by examining hundreds of design concepts and extracting strategies used by expert product designers [2,50]. The aim of this tool is to facilitate the generation of more diverse ideas than one would naturally produce. A designer may apply a heuristic from the DH cards to an existing idea, or a DH card might inspire an entirely new idea. The cards

Public Place Belongings Securer

Adaptively Framed		Innovatively Framed
Working in coffee shops and public places has become a common occurrence. Sometimes, however, it becomes necessary to step away for short periods of time to take a phone call or use the restroom. Once a workspace has been set up, it can be very inconvenient to pack it all away for these short absences. However, there is a danger of theft when leaving items in public places.	**Context** Same as neutrally-framed version	Working in coffee shops and public places has become a common occurrence. Sometimes, however, it becomes necessary to step away for short periods of time to take a phone call or use the restroom. Once a workspace has been set up, it can be very inconvenient to pack it all away for these short absences. However, there is a danger of theft when leaving items in public places.
Design a way for someone to secure several of his or her belongings in a public area to prevent theft quickly without disrupting the space. **Your solution should focus on improving existing designs or adapting familiar ways of approaching the problem or similar problems.** Consider constraints such as weight and size in your solutions, so users could carry it with them. Also think about how the solution would allow someone to secure several things of various sizes at one time.	**Need** Added criteria and constraints	Design a way for someone to secure several of his or her belongings in a public area to prevent theft quickly without disrupting the space. **Your solution should focus on creating totally new designs or developing totally new ways of approaching the problem.** Don't be concerned about a particular size or weight of your solution, and feel free to choose any materials you desire, as those sorts of constraints might be able to be worked out in the future.
Develop solutions for this problem. Focus on developing **practical** solutions. Try to develop solutions that are cost-effective and immediately workable. Be sure to write each solution on a different piece of paper, and use drawing to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.	**Goals** Explicit about types of ideas most valued	Develop solutions for this problem. Focus on developing **radical** solutions. Try to develop solutions without concern for cost or immediate workability. Be sure to write each solution on a different piece of paper, and use drawing to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.

Fig. 2 DPF: comparison of adaptive and innovative framings. Adapted from [3].

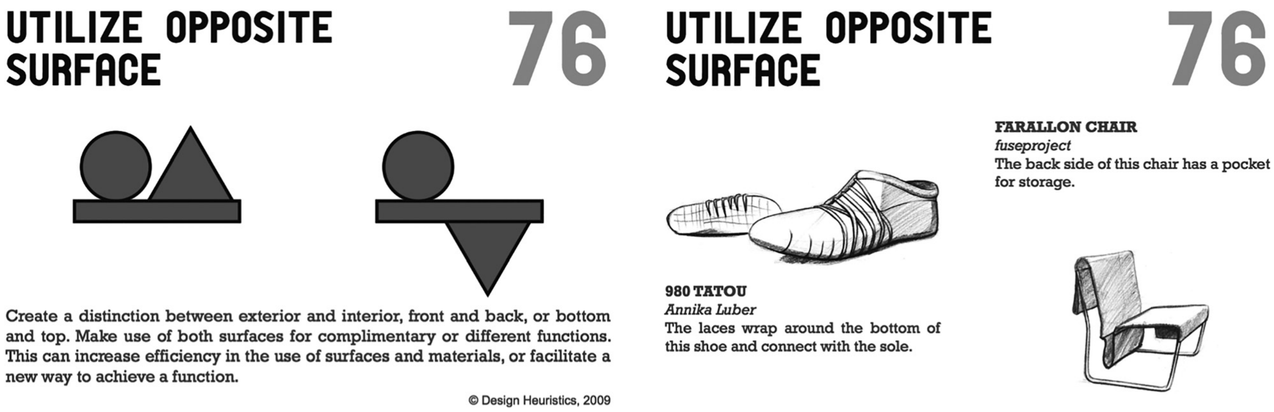


Fig. 3 An example of the 77 DH cards ideation tool (front and back of card #76) [2] (Reprinted with permission of Design Heuristics LLC, copyright 2009)

can be used in multiple ways, including facilitating the development of more radical or incremental ideas [2]. Our research continues to examine the potential impacts of this tool; the present study focuses on the impact of the 77 Cards on design concept quality.

Ideation Metrics. Many different metrics have been proposed to assess design concepts in ideation research, such as those developed by Dean et al. [7], Shah et al. [1,51], Besemer [52], and Ahmed and Fuge [53], all of whom used comprehensive literature reviews to suggest that quality, variety, novelty, and elaboration are important aspects of designs. A few studies have compared some of these metrics to see how closely they correlate [54]. In our larger body of work, we have analyzed concepts from our related, extended data set (which includes the data discussed here) using a range of ideation metrics, including those related to quality, novelty, variety, quantity, and paradigm-relatedness [5,6,33,35,54,55]. In this study, we constrained our focus to quality metrics alone to maintain a narrower focus, but other metrics will be featured in later, similar studies. The quality metrics utilized in this study are those presented by Dean et al. [7], who created a framework that organizes the various dimensions of quality metrics into categories (see Table 1).

Research Questions

Our first research question focused on the main effects of the cognitive style-based teaming, problem framing, and design heuristics interventions on ideation flexibility (as reflected in idea quality) across our sample:

RQ1: How does the quality of students' ideas differ between a neutral ideation session (i.e., control session—no intervention) and an intervention session (i.e., using cognitive style-based teaming, problem framing, or design heuristics)?

To determine if the effects of the three interventions were different depending on the cognitive style of the individual (i.e., if cognitive style moderates the results), the population was separated into three subgroups based on cognitive style: (1) individuals on the adaptive side of the cognitive style spectrum, (2) individuals in the middle range of the spectrum, and (3) individuals on the innovative side of the spectrum [16]. The following question guided the analysis for these cognitive style subgroups:

RQ2: How does the quality of students' ideas differ between a neutral ideation (control) session and an intervention session (ideation teaming, problem framing, or design heuristics) for students with a particular cognitive style (more adaptive, mid-range, or more innovative)?

Mirroring the research question for cognitive style, our third research question focused on the academic standing of the students at the time of their participation in the study. Academic standing is a form of cognitive level, which is independent of cognitive style [16]; cognitive level may also contribute to the characteristics of design ideas, leading to this research question:

RQ3: How does the quality of students' ideas differ between a neutral ideation (control) session and an intervention session (ideation teaming, problem framing, or design heuristics) for students of different academic standings?

Research Methods

Participants. The design concepts used in this study were collected from 171 undergraduate students in engineering and industrial design at the Pennsylvania State University and Iowa State University. Of these students, 20 were female and 151 were male; the large ratio of male to female students was an unanticipated condition based on the current enrollment in the relevant courses. Most of the students (122) were sophomores, 46 were first-year students, and three were juniors at their respective institutions. All of the sophomore and junior students (125 total) were from Iowa State University, enrolled in a sophomore-level mechanical engineering capstone class or a junior-level industrial design studio, respectively. The first-year students (46 total) were all from Penn

Table 1 Dean et al.'s quality metrics [7]

Relevance	Applicability	The degree to which the idea clearly applies to the stated problem
	Effectiveness	The degree to which the idea will solve the problem
Specificity	Implicational explicitness	The degree to which there is a clear relationship between the recommended action and the expected outcome
	Completeness	The number of independent subcomponents into which the idea can be decomposed, and the breadth of coverage with regard to who, what, where, when, why, and how
	Clarity	The degree to which the idea is clearly communicated with regard to grammar and word usage
Workability	Acceptability	The degree to which the idea is socially, legally, or politically acceptable
	Implementability	The degree to which the idea can be easily implemented

Table 2 Distribution of participants with respect to intervention, cognitive style, and academic standing

	Cognitive style-based teaming	Problem framing	Design heuristics	Totals
Totals	86	54	31	171
More adaptive	20	9	4	33
Midrange	22	12	8	42
More innovative	13	12	8	33
Unreliable KAI	31	21	11	63
First-year (PSU)	26	10	10	46
Sophomores (ISU)	60	41	21	122
Juniors (ISU)	0	3	0	3

State in a first-year introduction to engineering design course. These student samples were chosen and studied together based on the strong similarities among their disciplines from the design perspective across the two institutions. While the students were enrolled in three different courses in two departments, and the sample sizes were not even across all conditions, all of the students were focused on similar technical design principles, processes, and activities in the relevant courses at the time of the study. Our treatment of the various majors as a heterogeneous group aligns with previous work, including research conducted by Edelman [56], Sarkar and Chakrabarti, [57], Yilmaz et al. [58], and Sonalkar et al. [59].

Kirton's Adaption–Innovation Statistics and Groupings. A–I Theory is supported by the KAI® inventory, a research-backed and widely regarded psychometric instrument to measure cognitive style [16,23,60–62]. The KAI assesses one's preference for structure in ideation along a bipolar spectrum from highly adaptive to highly innovative. KAI scores follow a normal distribution in large general populations, with more adaptive individuals having lower scores and more innovative individuals having higher scores [16]. The mean KAI score for general population samples (across cultures) is 95 ($\pm$0.5) with a standard deviation of approximately 17 points, within a theoretical range of 32–160; the observed range is 45–145. Two thirds of all people fall between the scores of 78 and 112, and the vast majority (95%) fall between 61 and 129 [16].

In accord with certified KAI practice, only the students with reliable KAI scores as determined by ten standard psychometric reliability checks (e.g., less than three missing items, at least eight hard/very hard responses, less than ten midscale responses [16]) were included in the study; this resulted in a sample of 108 out of 171 students. Within this set and based on standard practice [16], relatively more adaptive, midrange, and more innovative samples were determined with respect to the mean (91.9) and standard deviation (14.9) of the resulting score distribution as a means to answer Research Question #2. In order to define subgroups that captured those who are more adaptive, more innovative, and midrange while avoiding small ($N < 20$) sample sizes, the groups were separated based on the mean plus or minus one-half of the standard deviation. Therefore, those with a KAI score of 99.4 or above were considered to be *more innovative* ($N = 33$), while those with a KAI score of 84.4 or below were considered to be *more adaptive* ($N = 33$). Those that fell between those values (i.e., $84.4 < \text{KAI} < 99.4$) were considered to be *midrange* ($N = 42$). Table 2 shows the distribution of participants across the three interventions, the two institutions, and all relevant subgroups (academic standing, cognitive style).

Data Collection: Ideation Sessions. The data collection sessions for this study were conducted as class activities that supplemented the course curriculum. Participation in the study was voluntary, and students were not rewarded or penalized for their willingness to participate. The timeline for a typical data collection session is shown in Fig. 4. Following a brief introduction to the study, students completed the KAI to assess cognitive style; KAI results were processed and analyzed by the research team after the session. After administering the KAI, the researchers shared a few best practices for ideation taken from the design literature with the students (e.g., generate many different ideas [11,63,64]) to facilitate their timely completion of the research activity.

Next, students generated ideas in response to one of four design prompts for 20 min with no intervention. We refer to this type of

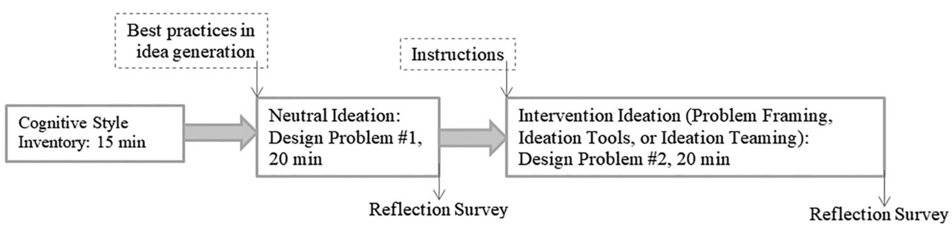


Fig. 4 Example flow of an ideation flexibility data collection session [4]

Table 3 Effectiveness metric scoring guidelines (Dean et al.) and rater training document for the public place belongings securer context

Score	Dean et al. level description	Rater training document
1	Solves an unrelated problem (it would not work, even if you could do it)	Does not offer alternative to storing items in public
2	Unreasonable or unlikely to solve the problem (it probably will not work)	Idea is otherwise unreasonable/unlikely to provide/allow/enable storing of items.
3	Reasonable and will contribute to the solution of the problem (it helps, but is only a partial solution)	If at least one but not all of the following criteria are met: • Mechanism is secure[a] • Idea can store multiple items • Mechanism quickly secures belongings • Mechanism does not disrupt work space
4	Reasonable and will solve the stated problem without regard for workability (if you could do it, it would solve the main problem)	If all four of the above criteria are met

[a]Secure: free from risk of theft.

idea generation as "neutral ideation," in which each person's natural preferred approach is used. These neutral ideation sessions served as our control condition (i.e., "control sessions"), while ideation that involved any of the interventions ("intervention ideation") served as our experimental condition (i.e., "experimental sessions" or "[teaming/problem framing/design heuristics] intervention sessions"). Students were asked to individually record each idea on a separate sheet of paper using sketches and written descriptions. Following a short break, the students received a *new* design problem and generated ideas for 20 min with one of the three interventions investigated in this study (i.e., teaming, problem framing, or design heuristics); in each case, appropriate instructions were provided for using any materials associated with the intervention (e.g., the 77 Design Heuristics cards). Across samples, the control sessions did not all utilize the same design problem; the same is true for the experimental conditions. After each session, students completed a brief reflection survey, which included questions related to students' perceptions of their ideas

Table 4 Sample public place belongings securer ideas and corresponding effectiveness scores with training document justification

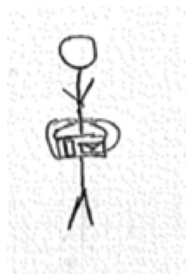
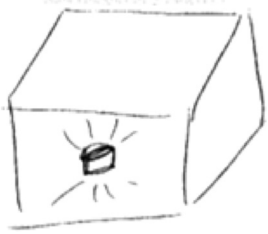
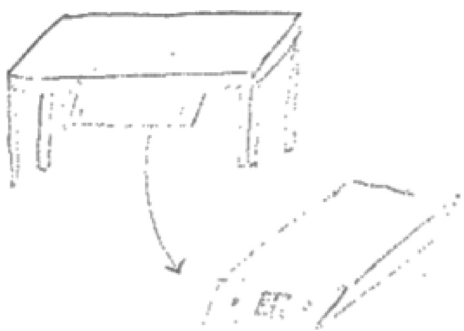
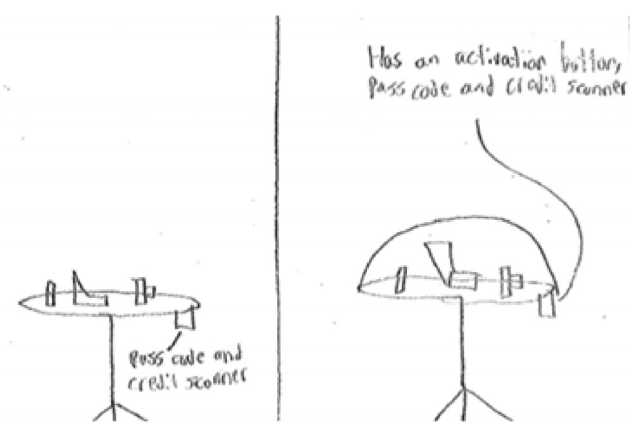
Score	Idea sketch	Idea description	Rater training document justification
1		Have employees carry a handy bag that carries there [sic] personal items in case they need to step away from their shift to make a phone call.	Does not have anything to do with storing personal stuffs
2		A motion sensored [sic] alarm system so that if anyone came in a few inches of the stand it would go off. This device could be turned on/off	Unreasonable to solve the problem—the alarm only warns the thief, does not have anything to protect the personal stuffs
3		It is a drawer under a table with electronic locks The user just has to place all of his/her belongings in the drawer and set a 4-digit pin code. Mechanism-slider for the drawer and an electronic lock	• It is secure and can store multiple items • It secures in short time • But, user needs to move stuffs to the drawer—disrupts work space
4		Table dome: A small dome will incase [sic] your table with your belongs till you return	• It is secure • Idea can store multiple items • Secures in short time—easy to use • Does not disrupt work space—do not move anything while you leave

Table 5 Paired t-test for teaming intervention's main effect on implicational explicitness and clarity scores (RQ1)

Sample	N	Implicational explicitness Mean	Clarity Mean
Neutral	86	2.042	2.398
Teaming	86	1.835	2.277
		p-value: 0.003	p-value: 0.044
		T-value: 3.11	T-value: 2.04
		Power > 0.99	Power = 0.75

Table 6 Paired t-test for design heuristics intervention's main effect on implicational explicitness scores (RQ1)

Sample	N	Implicational explicitness Mean
Neutral	31	2.124
Design heuristics	31	1.835
		p-value: 0.008
		T-value: 2.83
		Power = 0.96

and their ideation processes. An analysis of the survey results is outside the scope of this paper, but some related analyses can be found in our other works [5,6,34].

The teaming intervention involved students working together in dyads (with an occasional team of 3) to generate ideas; of the 171 student participants, 86 of them completed the teaming intervention (see Table 2). In the framing intervention, students were randomly assigned to either the adaptive or innovative problem framing condition [4]; another 54 students completed the framing intervention. For the design heuristics intervention, students were given the same ten DH Cards to use as they generated ideas [4]; the final 31 students used the design heuristics intervention.

Assessment of Students' Design Ideas. Six of Dean et al.'s well-established quality metrics (see Table 1) were used in this study (i.e., applicability, effectiveness, implicational explicitness, clarity, acceptability, and implementability). The completeness metric was excluded due to poor inter-rater reliability in its assessment; the raters found it difficult to clearly define the "who, what, when, where, why, and how" of this metric. For example, "what" could be interpreted as: What does the user do? What does the design do? What is the design? What are the parts of the design? Additionally, confusion arose about whether statements can and should fall into multiple categories: i.e., can one section of an idea description address both "how" and "what?"

Our research team developed a rater training document to serve as a guideline for assigning metric values. This document aimed to explain how the raters should authentically apply Dean et al.'s metrics to the ideas generated for our problem contexts. Subsequently, the training document allowed future raters to follow the same guidelines and reproduce the methods and interpretations from the original rating team. The rating guidelines helped ensure

Table 7 Paired t-test for teaming intervention's effect on more adaptive students' implicational explicitness and clarity scores (RQ2)

Sample	N	Implicational explicitness Mean	Clarity Mean
Neutral	20	2.218	2.590
Teaming	20	1.864	2.333
		p-value: 0.026	p-value: 0.009
		T-value: 2.42	T-value: 2.91
		Power = 0.94	Power = 0.75

Table 8 Paired t-test for teaming intervention's effect on mid-range (style) students' implicational explicitness scores (RQ2)

Sample	N	Implicational explicitness Mean
Neutral	22	2.080
Teaming	22	1.727
		p-value: 0.028
		T-value: 2.37
		Power = 0.96

that the quality of an idea's features was being measured instead of the quality of the presentation—except for the clarity metric, which specifically scores the clarity of an idea sketch and its written description. As an example, Tables 3 and 4 show Dean et al.'s effectiveness metric with the related training document scoring guidelines, as well as sample ideas, scores, and justifications, respectively. Details of the rubrics for all six quality metrics used here are also provided in Ref. [55].

The idea raters were eight undergraduate and graduate engineering students who had taken project-based engineering design courses prior to this study; they were paired to establish reliability. Raters first familiarized themselves with the problem contexts and the quality metrics. To demonstrate strong inter-rater reliability for a given metric, raters evaluated a preliminary set of 50 design ideas independently; these ideas were not used as data in this study. After raters completed this initial assessment, they compared their results for inter-rater reliability using Cronbach alpha scores. If the Cronbach alpha score was greater than 0.7, then reliability was considered sufficient; otherwise, raters determined discrepancies and tried again with a new set of 50 design ideas. This method for demonstrating reliability was previously implemented by Teerlink [65].

Idea scores for each participating student were combined so that each student had an average score for each metric for their control and experimental sessions, respectively. For the teaming intervention, while students generated ideas together, each student sketched and described his/her personal version of each idea they discussed on a separate sheet of paper. Therefore, team members' ideas were scored individually rather than as a team. By examining how these metric scores varied for each student for each intervention, we hypothesized that some degree of ideation flexibility might be detected. In other words, if an individual's metric scores differ between ideating neutrally and ideating with an intervention, then some degree of ideation flexibility may be at play. On the other hand, if an individual's metric scores do not differ between ideating neutrally and ideating with an intervention, then ideation flexibility is not evident.

Results

The three research questions were investigated using paired t-tests and Pearson correlations (via MINITAB), with a significance level of 0.05 across all tests. This section discusses those research questions in the following order: (1) main effects of the three interventions; (2) effects of the three interventions for students of different cognitive styles; and (3) effects of the three interventions for students of different academic standings. An a priori power analysis based on other data sets for the six quality metrics indicated a minimum sample size of 27 for a statistical power value of 0.8 for each test (effect size = 0.25; SD of paired differences = 0.44). Since this minimum sample size was not available for every desired test in this study, the actual post hoc power values of the tests that yielded significant results are reported in the appropriate tables.

Main Effects: RQ1. The problem framing intervention sessions did not exhibit any statistically significant differences in

Table 9 Correlations for clarity, implicational explicitness, and KAI for neutral ideation (RQ2)

	Clarity	Implicational explicitness
Sample (N)	108	108
Pearson correlation coeff.	−0.239	−0.286
p-value (Power)	0.013	0.015
Power	0.71	0.86

design idea quality as compared to the control sessions over the full sample, while the teaming intervention led to a decrease in average implicational explicitness and clarity, and the design heuristics intervention led to a decrease in average implicational explicitness. Specifically, as shown in Table 5, the average implicational explicitness and clarity scores were higher for the control session than for the teaming intervention session by approximately 10% and 5%, respectively. In Table 6, the average implicational explicitness scores were also higher for the control session than for the design heuristics intervention session by approximately 15%. As a reminder, clarity and implicational explicitness are subdimensions of specificity according to Dean et al. [7] (see Table 1). These results indicate that for this participant sample, the design ideas generated in the teaming intervention sessions lost some specificity in terms of how they solve the given problem, while ideas generated in the design heuristics intervention sessions saw a loss of implicational explicitness only.

Implicational explicitness and clarity are each measured on a scale from 1 to 3; the mean values shown in Tables 5 and 6 indicate the difference in average scores from neutral ideation to ideation with the interventions. These statistically significant decreases may indicate that some students are changing the specificity of ideas they generate in the presence of another student or while using the DH cards—i.e., exhibiting ideation flexibility—although such causation cannot be assumed without further investigation.

The lack of statistically significant differences in idea quality for the problem framing intervention suggests that, across individuals, while the framing may have impacted other idea attributes, it did not impact quality as measured by the metrics considered in this study. This finding may be a result of the sample size, the fact that two different types of problem framings (more adaptive and more innovative) were involved, or the fact that this intervention does not play a role in quality specifically but may be better used for targeting other idea attribute changes, such as paradigm-relatedness.

Cognitive Style Results: RQ2. For the cognitive style-based teaming intervention, statistically significant differences also appeared in the quality metrics when the general sample was divided by cognitive style into smaller samples. Table 7 shows that, for the more adaptive students, both implicational explicitness and clarity scores decreased with the teaming intervention by 16% and 10%, respectively. Compared to the main effect of teaming on idea characteristics, this result for the more adaptive thinkers shows similarities and differences. First, implicational explicitness and clarity are again higher in the control session than in the teaming intervention session. However, the size of the difference is larger (by approximately 5%) when only the more adaptive thinkers are considered. Students in the mid-range cognitive style subgroup also displayed a decrease in implicational explicitness scores under the teaming intervention, as shown in Table 8; however, they did not show a decrease in clarity scores. Students in the more innovative subgroup did not exhibit statistically significant differences in any of the six quality metrics.

Table 10 Paired t-test for design heuristics' effect on more innovative students' clarity scores (RQ2)

Sample	N	Clarity Mean
Neutral	8	2.075
Design heuristics	8	2.546
		p-value: 0.020
		T-value: −3.00
		Power = 0.77

Consistent with A–I theory, the results also show that the more adaptive thinkers, midrange thinkers, and general sample (which includes the more innovative thinkers, who did not return significant results for this metric) had the highest, middle, and lowest mean scores for implicational explicitness in the control sessions, respectively. Specifically, A–I theory posits that the more adaptive an individual is, the more attention they will naturally pay (as a result of their cognitive style) to the alignment between a solution and the problem that solution is designed to address [16]. In essence, the more adaptive a person, the more implicationally explicit and clear their ideas are likely to be by virtue of their cognitive style. Examining correlations between KAI and the six quality metrics helped confirm this theoretical assumption. There were weak ($r \leq 0.3$) negative correlations between KAI and clarity and between KAI and implicational explicitness for ideas generated during the control sessions (see Table 9). For KAI, negative correlations amount to a correlation with Adaption (as the "lower end" of the A–I score spectrum). While not strong, these correlations are consistent with the results shown in Table 7. More adaptive thinkers—i.e., those with lower KAI scores—tended to offer ideas with higher scores for clarity and implicational explicitness, even when the scores for those metrics decreased from a control session to a teaming intervention session. In more general terms, the data suggest that more adaptive thinkers have higher implicational explicitness and clarity scores in control sessions than other people. Despite the fact that their scores for those metrics decrease when they work in a dyad, the correlation indicates that more adaptive students still tend to have higher scores for implicational explicitness and clarity than their midrange and more innovative counterparts.

With these results, we can conclude that the teaming intervention affects the quality of the ideas generated by the more adaptive and midrange thinkers in similar (though not identical) ways and yet does not seem to affect the quality of the ideas generated by the more innovative thinkers in any significant way. One possible explanation for this is that when generating ideas in a dyad, adaptive and midrange thinkers are more willing (based on their underlying cognitive preferences for structure) to ideate like their more innovative partner than a more innovative thinker would be willing to ideate like an adaptive partner.

The design heuristics intervention showed one significant effect on the quality metrics for the generated ideas based on cognitive style. Interestingly, here, the more innovative participants' ideas show a statistically significant *increase* in clarity (23%) from the control session to the design heuristics session, as shown in Table 10. A possible explanation for this result is that a more innovative thinker's ability to clearly express his/her ideas may actually benefit from having concrete examples to reference, such as those provided by the DH cards. Here, it is important to note the small sample sizes (all $N < 10$ for the more adaptive, midrange, and more innovative cognitive style subgroups within the total sample of 31) for this intervention.

Academic Standing Results: RQ3. Finally, for the samples linked to academic standing, the teaming and design heuristics interventions again provided statistically significant differences. For the first-year students, Table 11 shows how the implicational explicitness and clarity scores of their ideas both decreased from the control session to the teaming intervention session, which aligns with the main effect. Likewise, the sophomores'

Table 11 Paired t-test for teaming's effect on first-year students' implicational explicitness and clarity scores (RQ3)

Sample	N	Implicational explicitness Mean	Clarity Mean
Neutral	26	2.262	2.518
Teaming	26	1.920	2.330
		p-value: 0.019	p-value: 0.038
		T-value: 2.51	T-value: 2.19
		Power = 0.98	Power = 0.6

Table 12 Paired t-test for teaming's effect on sophomores' effectiveness and implicational explicitness scores (RQ3)

Sample	N	Effectiveness Mean	Implicational explicitness Mean
Neutral	60	2.949	1.948
Teaming	60	3.200	1.792
		p-value: 0.007	p-value: 0.049
		T-value: −2.81	T-value: 2.01
		Power = 0.97	Power = 0.83

implicational explicitness scores decreased with teaming (see Table 12). Interestingly, however, the sophomores' effectiveness scores *increased* from the control session to the teaming intervention session, which is unique within the context of this study. This result is interesting in two ways: (1) it does not follow the main effect; and (2) it suggests that a higher cognitive level (as represented here by a higher academic standing) may lead to more effective design ideas regardless of other individual differences (e.g., cognitive style). Here, sophomore student dyads showed changes in their design ideas that differed from their first-year counterparts. It is possible that the first-year students' relative lack of engineering experience may have precluded them from producing ideas in teams that were more effective than their individual ideas. On the other hand, when sophomore students worked in dyads, the pairs generated ideas that were significantly more effective than their individual ideas. As shown in Table 13, the design heuristics intervention also provided significant results for first-year students, following the main effect with respect to implicational explicitness (i.e., scores decreased from the design heuristics intervention session to the control session).

Discussion

Developing effective design interventions opens up many opportunities to enhance and improve the ideation of engineers if those interventions can be shown to have an impact. The results of this study indicate that, of the three interventions we applied (teaming, problem framing, and design heuristics), teaming generated the most noticeable and statistically significant effects on the quality characteristics of design ideas. Specifically, our results show that working in teams decreased the generated ideas' implicational explicitness and clarity scores as a main effect. However, different relationships also grew out of our exploration into the teaming intervention, including the negative correlations between KAI and clarity and implicational explicitness scores, and an *increase* in the effectiveness scores of ideas for sophomore students working in teams.

Table 13 Paired t-test for design heuristics' effect on first-year students' implicational explicitness scores (RQ3)

Sample	N	Implicational explicitness Mean
Neutral	10	2.387
Design heuristics	10	1.782
		p-value: 0.001
		T-value: 4.56
		Power = 0.98

To some extent, our findings mirror the mixed results related to design team performance found in the literature, where some studies show teams developing more (and more diverse) ideas than individuals [66,67], while others show teams experiencing productivity losses instead [68,69]. In many of these previous investigations, the assessment of team performance has focused on simple measures, such as the number of concepts generated or general (and often subjective) creativity metrics. Likewise, our findings are somewhat similar to those of several design-related studies involving ideation and other personality frameworks (e.g., Jung's psychological types), in which statistically significant correlations were found between various ideation metrics and some dimensions of the Myers–Briggs type indicator [70,71]. Nevertheless, in our previous work [34,65,72] and the new work presented here, we have taken the investigation of teams in novel directions by applying a wider variety of more carefully defined metrics and by expanding our analyses to include aspects of deep-level human diversity, such as cognitive style.

Decreases in implicational explicitness and clarity scores may lead to the misconception that ideas arising from a team are "worse" than those that stem from working alone, but care must be taken with such an interpretation. Hypothetically, one team may offer ideas that are less clear but more effective and acceptable for a particular design problem, whereas another team's ideas are less explicit but more implementable and applicable—i.e., the overall idea quality decreased in one metric but increased in two others. In addition, lower levels of implicational explicitness and/or clarity might occur because the designers involved are actually exploring the design space in new ways by moving into sectors where more questions exist about what is possible, leading to trade-offs in quality. Finally, specific expectations about a solution should also be considered in evaluating whether certain ideas are "better" or "worse" than others based on these metrics. For example, in an innovatively framed problem, participants are urged to think "out of the box," which could mean that ideas do not need to be as implicationally explicit or clear as they would if it were a neutrally framed problem.

While the design heuristics and problem framing interventions showed fewer statistically significant relationships related to idea quality in this particular study than the teaming intervention, other studies done by this research team have shown significant impacts on other ideation outcomes from these two interventions. One study specifically examined the effects of the design heuristics intervention on variety scores evaluated with variety trees; there, we found that ideas generated with the DH cards scored lower on the variety tree evaluation than those generated in a control session [35]. This is in contrast to other studies on the impact of design heuristics on idea diversity, e.g., Ref. [2]. A pilot study examined the three interventions in ways similar to the current study but did not distinguish between people of different cognitive styles or academic standings. That study found that effectiveness and acceptability scores increased for ideas generated in the adaptive framing intervention, and clarity scores increased for ideas generated in the innovative framing intervention [55]. The problem framing intervention may be more likely to directly impact metrics related to cognitive style rather than cognitive level. For example, our work has shown how various types of problem framing interventions can impact the paradigm-relatedness of ideas [5,6,33]. Furthermore, the problem framing intervention may impact ideation differently with an adaptive framing as compared to an innovative framing, and so there may not be a clear overall impact on ideation across the problem framing intervention as a whole.

Implications

Several implications for engineering design education and practice emerge from this work. First, the fact that statistically significant results were found between cognitive style and idea quality across two design interventions suggests that individual cognitive style differences do play a role in how students approach ideation. This result proves the importance of tailoring idea generation pedagogy to complement variations in cognitive styles across students and to consider the effects of cognitive style on student performance when assessing idea generation outcomes in the classroom.

Another implication of this study is the impact of design interventions on student ideation quality. Rather than relying on hands-off approaches in ideation pedagogy (individual brainstorming), this study demonstrates how interventions, even in 20 min timeframes, can change the characteristics of the solutions offered by the students. Although there is evidence of the influence of design interventions on idea quality, a clearer understanding of those effects as measured by the characteristics of the ideas (this study) or by other methods is needed. Such clarity can inform how and when interventions should be implemented with engineers (both students and practitioners), what improvements can be made to design interventions, and why one intervention may be more useful for a certain type of participant than another.

Limitations and Future Work

One limitation of this study was the uneven and sometimes small sample sizes, which were a function of several factors, including the elimination of participants with unreliable KAI scores and uneven enrollments in the courses involved. While the full sample of 171 students was relatively large for a study of this type, the sample sizes decreased when each intervention was isolated for study. When the samples were separated based on cognitive style (and reliable KAI scores) or academic standing, the sample sizes became even smaller. As a result, the power of our statistical tests varied, with several achieving less than the desired 0.8 value; these particular tests should be revisited with larger sample sizes in future work.

Next, in studying differences between ideas generated in the control and experimental sessions, we assumed that the influence of priming for ideation was negligible; this assumption should be investigated more closely in future work. Also, this study did not examine relative conditions within the interventions. For instance, with the teaming intervention, we examined generally how the presence of any team member affects another team member's quality of ideas without taking their relative cognitive styles into account. In other words, we did not explore the effects of any cognitive style gaps that might have existed between teammates; however, other studies in our larger body of work have investigated the effects of these gaps [34,72]. Additionally, students did not participate more than once, so this study does not explore the effects of one person working with different partners within the teaming intervention.

Due to the limited number of paired raters in our research group with sufficiently high inter-rater reliability, we have not yet evaluated the quality of all the design concepts collected as part of this project (over 3000 concepts); the ideas examined here represent approximately one third of the full data set. For instance, there are several samples of high school students in summer design programs whose design concepts have only been evaluated in studies investigating paradigm-relatedness. While we are satisfied with the samples selected for this study, we intend to conduct further tests with additional samples in the future as they become available. Finally, different metrics may be more or less "sensitive" to the effects of different design interventions, so while certain metrics may indicate no change from ideating neutrally to ideating with an intervention, there may be other metrics not considered in this study that would clearly show those shifts.

Conclusions

Our work demonstrates that teaming, which has long been considered simply a "fact of life" (and often an unpleasant duty) in design, should be reconsidered as an actual *tool* for targeted ideation intervention. In other words, designers should be taught how to generate ideas in teams not simply to expand their pool of ideas generally, but to expand those ideas in specific ways. Based on the results of this study, along with our previous results for the effects of cognitive style in teaming [34,65], we conclude that research into teaming as a targeted intervention for design ideation should be expanded and deepened using more/other design metrics, more/other cognitive measures, and more/other types of design activities (e.g., concept selection, prototyping).

The key limitation of this study—uneven samples—has been partially addressed through power analyses, which show that many of our results remain significant, even with small sample sizes. Still, additional confirmatory studies should be completed to support these results as additional data become available, in addition to repeating studies with smaller power values. In particular, the finding that sophomores were more effective in teams than first-year students appears to be robust, but it still warrants further investigation with more participants taken from one university to ensure that the results can be replicated and to explore whether this result extends to other outcome metrics, such as novelty or variety.

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