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Distributed Ideation: Idea Generation in Distributed Capstone Engineering Design Teams*

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This paper documents two studies in distributed idea generation at Texas A&M. The first study is a controlled two-factor experiment wherein three-person groups of mechanical engineering capstone design students generate solutions to a simple design problem using either brainstorming or a modified 635 method in either a distributed or collocated team. Eight groups participated in the experiment; two were assigned to each of the four experimental conditions. The ideas produced are evaluated in terms of quantity, quality, novelty, and variety, using a series of metrics described in the paper. The modified 635 method produced the highest quantity of non-redundant ideas; the team's distribution had no significant effect on the number of ideas they produced. Distributed teams using the modified 635 method generated the highest quality ideas, while collocated teams using the same method produced the most variety. Collocated brainstorming teams generated the most novel ideas. The other study presented in this paper documents the performance of two globally distributed Mechanical Engineering capstone design teams. These student teams are composed of members from Texas A&M College Station and Texas A&M Qatar in Doha Qatar. The two teams participate in a controlled ideation experiment to generate possible solutions to their respective design problem; a third team with all its members in College Station also participates in the experiment. The teams generate ideas using the modified 635 method. This experiment confirms that the modified 635 method is a viable ideation technique for distributed teams and seems to confirm that the quantity of ideas generated with the method is not dependent on the team's distribution. Furthermore, instructors for the globally distributed teams observe that the teams performed on par with typical collocated capstone design teams.

Keywords: idea generation; ideation, distributed teams; capstone design; brainstorming; method 635

1. Introduction

Engineering is, and is becoming increasingly more so, a physically and culturally global activity [1]. Project teams are often comprised of engineers from different countries, with different primary languages and cultural perspectives on projects [1]. As with practice, engineering education is becoming more global [2]. Nevertheless, engineering education remains a more regional activity than engineering practice [3]. Even in cases where the classroom is culturally diverse, students are typically still physically collocated.

In engineering practice, management staff, engineering teams, and customers can all be globally distributed. By contrast, capstone engineering design students typically work with a project sponsor and customer in the same or a nearby time zone. Whereas in engineering practice problem clarification may evolve slowly through an email thread or threads, students can sit in the same room at the same time as they articulate design needs, requirements, and constraints. In engineering practice, solutions and concepts are generated individually. As part of a capstone class, students are able to share a common blackboard as they dynamically interact to generate ideas.

Like practicing engineers, students continue to use a greater degree of connectivity media such as email and cell phones to work together on projects. Even so, students share a common workday and work week. As a result, responses to text messages and emails are typically received in minutes or hours. A common workday and workweek offers students other advantages over distributed teams, such as the opportunity for spontaneous meetings, easier management of schedules and deadlines, and increased motivations from regular, face-to-face meetings.

Distributed and collocated engineering design teams possess different advantages and strengths [3]. Nevertheless, transitioning from a collocated engineering design experience to a distributed one can pose a challenge for new engineers [3]. To better prepare students for the distributed nature of engineering practice, the College of Engineering at Texas A&M University is developing a globally distributed capstone engineering design course. Recently, Texas A&M's Mechanical Engineering department offered a globally distributed capstone design course. Two student design teams were formed with students collaborating between Texas A&M College Station (TAMU-CS) and Texas A&M Qatar (TAMU-Qatar) in Doha Qatar.

These globally distributed design teams were an ideal vehicle to investigate idea generation techni-

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ques in a distributed engineering design team. Three design teams took part in a controlled ideation experiment. The teams generated ideas using a modified 635 method. The results of this experiment indicate that the modified 635 method is a suitable ideation method for distributed teams, enabling design teams to produce similar numbers of ideas irrespective of the team's distribution.

The globally distributed design teams allowed us to investigate ideation within a distributed team in a very realistic setting but the collected data is insufficient for a detailed, quantitative analysis. A more extensive experiment, conducted at TAMU-CS, compared distributed and collocated teams generating ideas using a brainstorming technique and the modified 635 method.

The ideas generated in the second ideation experiment are evaluated in terms of quantity, quality, novelty, and variety [4]. Teams using the modified 635 method generated the highest quantity of ideas, regardless of the teams' spatial distribution. The highest quality ideas were produced by distributed teams using the modified 635 method. Collocated brainstorming promoted the most novel ideas, while the collocated modified 635 method generated the greatest variety.

The remainder of this paper is organized into four sections: background, research approach, results and discussion, and a conclusion. The background section summarizes prior research into distributed teams, brainstorming, and several brainsketching techniques. The research approach section explains how two experiments were performed and how the experimental results are evaluated. The fourth presents experimental results and discusses their more significant implications. The conclusion summarizes findings and discusses the implications of this research for engineering instruction.

2. Background

2.1 Distributed teams

Distributed teams are those teams that are dispersed geographically and/or temporally. Extending the concept of distributed teams, virtual teams are teams that 'cross time, space, and cultural boundaries and do so effectively with the use of technology' [5]. Researchers in psychology, sociology, and business management have drawn from their knowledge on collocated teams to research processes in virtual teams, and have reevaluated concepts such as team building and trust development, communication, and team management in this context [6–14]. An extensive literature review did not find similar studies on engineering, though many of the teaming, trust, and communication topics should be similar for multiple disciplines.

Though global virtual teams offer advantages, these teams also face more challenges than collocated teams or teams that are distributed either only spatially or only temporally. Barczak and McDonough [15] compare the challenges of traditional, collocated product development teams to global virtual teams.

The main challenge for teams dispersed only geographically is that the members are not in physical contact with each other. Building trust and establishing the team is harder than in collocated teams. Members of geographically and temporally distributed teams face additional challenges in scheduling meetings. Differing workweeks and holidays make meetings even more problematic for global virtual teams.

Multiple researchers have identified success factors for globally distributed teams. Barczak and McDonough [15] suggest that teams hold a face-to-face kickoff meeting, increase communication amongst members, and hold regular progress-update meetings. Jarvenpaa and Leidner [10] add that the team manager should select members for responsibility, dependability, and self-sufficiency. Thomson et al. [16] identified four key elements that increase the effectiveness of virtual teams: a distributed process map showing how to design in a virtual team, a uniform message management system, 'best practice' guides to streamline the appearance of exchanged information, and use of the company intranet to contact in-house experts when assistance is needed. Lee-Kelley and Sankey have similar suggestions for design in virtual teams [11].

2.2 Idea generation methods

Though generating ideas to solve problems is important to many team-based activities, idea generation is central to engineering design. Many methods have been developed to produce preliminary solutions during the conceptual design phase, including brainstorming, the 635 method, the gallery method, C-sketch, and morphological searches based on functional analysis [17]. Research on brainstorming and its variations is abundant compared to the amount of research on other idea generation methods [18–24]. Beyond brainstorming, there has been research on gallery writing versus pool writing [25]; the use of verbs as stimuli in concept generation [26]; a survey of several creativity techniques developed in Germany [27]; and a new technique called C-sketch [28]. Several of these methods are briefly reviewed here as they are relevant to the distributed ideation experiments reported by this paper.

Osborn developed brainstorming to improve the creative problem solving process, especially the number of ideas generated [24]. During brainstorming, a recommended eight to ten people verbally describe their ideas. Osborn developed four basic rules to be followed during a brainstorming session.

1. *Criticism is ruled out.* Adverse judgment of ideas must be withheld until later.
2. *'Free-wheeling' is welcomed.* The wilder the idea, the better.
3. *Quantity is wanted.* The greater the number of ideas, the more the likelihood of useful ideas.
4. *Combination and improvement are sought.* Participants should suggest how ideas of others can be turned into better ideas; or how two or more ideas can be joined. [29].

Electronic brainstorming lets brainstorming participants enter ideas into a computer that displays the ideas on all the participants' screens [30–31]. The benefits of electronic over verbal brainstorming are anonymity, parallel communication, and automatic record keeping [30].

Shortly after the publication of Osborn's book on brainstorming, researchers began examining the claim that brainstorming increases the number of ideas generated. An early study by Taylor et al. [24] compared the ideas generated by brainstorming groups to those by sets of individuals brainstorming independently, so-called 'nominal groups.' The study found that brainstorming groups had a lower mean number of ideas, mean number of non-redundant ideas, and quality of ideas than the nominal groups. Both Diehl and Stroebe [32] and Mullen, Johnson, and Salas [33] confirmed Taylor et al.'s findings.

Parnes and Meadow found evidence to support Osborn's theory that a higher quantity of ideas will lead to a higher quality of ideas [34]. Diehl and Stroebe [32] and Adánez [18] conducted experiments that support Osborn's hypothesis that quantity generates quality. However, Briggs et al. found that if a team produces more ideas, it will produce more low quality ideas, but not necessarily more high quality ideas [35]. Mullen et al. found that brainstorming leads to both a quantitative and qualitative loss in generated ideas [33].

The second idea generation technique used in this study is a modified 635 method. This ideation method was developed by combining several brainsketching and brainwriting methods. The term brainwriting is a generic term comprising all idea generation techniques that use written statements, as explained by Geschka [27] and VanGundy [36]. Brainsketching is an adaptation of brainwriting, using sketches instead of or in addition to written words [37]. The modified 635 method incorporates elements from the 635 method, the gallery method, and C-sketch.

The 635 method is a brainwriting technique developed by Rohrbach in the 1970's [17, 28, 38, 39]. It was developed for six participants, but can easily be adapted for a different number. Each participant is given a piece of paper, and asked to write down (not sketch) three initial solutions to a design problem during a five-minute interval; afterwards, each sheet of paper is passed on to a neighbor. For the next five minutes the participants then try to add to the existing solutions or to come up with new ideas before passing the sheets again in the same direction. For six participants there are five exchanges.

The 635 method has some benefits compared to brainstorming: no moderator is needed, all participants can generate ideas simultaneously, the ideas are automatically recorded, each idea is refined as it circles through the participants, and disruptive arguments are less likely. However, participants might feel more isolated and the stimulation through the written ideas might not be as intense as with voiced ideas.

The 5-step brainsketching gallery method was presented by H. Hellfritz in 1978 [17]. First, the session leader presents the design problem. Each participant then has 15 minutes to generate ideas individually and to express them in annotated sketches. For the next 15 minutes, the participants examine and discuss all ideas generated thus far. In the fourth step the participants individually write down all ideas that arose through the previous discussion. Finally the participants complete, categorize, and evaluate all created ideas. The gallery method has the same advantages over brainstorming as the 635 method. In addition, it encourages sketches, which work well in technical design problems, and allows discussion among the participants.

Collaborative sketching (C-sketch), also known as 5-1-4 G, was first presented in 1993 by Shah [28, 40]. In C-sketch, five designers create one sketch each on a blank sheet of paper and pass the sheet on four times, adding content each time as in the 635 method. Only sketching is allowed, no written or verbal annotations are permitted. Shah et al. compared 635 method, the gallery method, and C-sketch and found that C-sketch produced more ideas than 635 method and more novel and varied ideas than the gallery method [28].

In this study, a modified 635 method is used. It is based on the 635 method exchange schedule and uses the idea of developing three ideas during each time interval. However, inspired by C-sketch and its advantages over 635 method [28], the participants are encouraged to sketch and annotate their ideas. The sketch surface is partitioned in three similarly sized areas allowing the development of three ideas at the same time, each one in a spatially separated area. Whereas each participant has three personal fields to add comments or new ideas in the original 635 method, in the modified 635 method the participants are encouraged to sketch and annotate on top of the three initial ideas produced in the first interval.

3. Research approach

This paper presents results from two ideation experiments: the Controlled Study and the Capstone Study. In the Controlled Study, capstone design teams at Texas A&M College Station participated in a two-factor controlled ideation experiment employing brainstorming and the modified 635 method in collocated and distributed teams. In the Capstone Study, members of two globally distributed design teams and one collocated team used the modified 635 method to generate ideas relevant to their respective design problems. This section presents the goals and design of each experiment as well as their metrics.

3.1 Controlled study

The Controlled Study investigates the effects of team distribution on the ideas generated using brainstorming and the modified 635 method. The generated ideas are evaluated using metrics for quantity, quality, novelty, and variety.

3.1.1 Controlled study research questions

Conventional idea generation methods are designed for collocated teams. This study evaluates how a design team's distribution influences the ideas its members generate. The results of this experiment are evaluated using four metrics proposed by Shah et al. [28] and refined by Linsey et al. [41]: *quantity*, *quality*, *novelty*, and *variety*. This experiment is designed to answer the following questions:

- Does brainstroming produce ideas of higher quantity, quality, novelty, or variety than the modified 653 method?
- Do collocated teams produce ideas of higher quantity, quality, novelty, or variety than distributed teams?
- Is there any interaction between the idea generation method and the design team's distribution?

3.1.2 Controlled study experimental design

Four conditions are in this two-factor study. Two conditions employ brainstorming while the other two use the modified method 635 and for each ideation technique, one condition requires a distributed team and the other a collocated team. Schmidt provides a detailed description of the experimental design [3].

3.1.3 Controlled study materials

The experiment takes place in a windowless 5m x 3m room. For the distributed brainstorming condition, one or two team members, depending on team size, were placed in an adjacent room to simulate a spatially distributed design team. The students use Wacom Cintiq 21UX pen displays instead of writing and sketching on paper to allow all cursor movements and executed commands to be recorded with Camtasia, a screen recording program. Microsoft Office OneNote is used as sketchpad. A projector is used for brainstorming exercises with collocated teams to make sure all teammates can see the sketchpad. Camtasia also captures the conversation amongst the collocated team members. Distributed teams use the Saba Centra conferencing tool to share desktops and make conference calls. Each participant uses a headset with headphones and microphone, allowing Saba Centra to record any verbal communication that took place among the distributed team members.

3.1.4 Controlled study experimental procedure

The experiments are run one team at a time. After informed consent, the participants are randomly assigned a computer workplace equipped with a tablet screen. If the teams are working in simulated distributed teams using a modified 635 method, all team members are in the conference room and dividers are used to prevent any team member from seeing other team members. In addition to these measures, in the distributed brainstorming condition, one or two team members use an adjacent windowless office to minimize acoustic interference. In the collocated modified 635 method condition, the tables are arranged in a diamond so that the participants can see each other, but cannot look at each others' screens. In the collocated brainstorming condition, the team sits around a round table.

A 10-minute training session is used to get a feeling for the pen and writing on the tablet. Next, each participant turns over an instruction sheet on the participant's workplace. The instruction sheet shows a short explanation of the idea generation technique that is read to the participants by the experimenter [4]. Underneath the information sheet, the individuals receive the design problem, a copy of which is provided in Fig. 1. The design problem is read to the participants. The participants are repeatedly asked whether they have any questions about the problem statement. Questions are answered without giving solutions to the ideation

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Fig. 1. Peanut sheller design problem statement for the Controlled Study.

task. After all questions are answered, idea generation begins.

The brainstorming ideation session lasts for 35 minutes. The initial idea generation session for the modified 635 method lasts 15 minutes and the subsequent sessions last 8 minutes each. The experimenter warns the participants five minutes prior to the end of a brainstorming session or one minute prior to the end of a modified 635 method session. The experimenter reads a script to give a standard instruction set to the participants [4].

The screen recordings for the second distributed modified 635 method team started about 2 minutes into the initial idea generation phase; the startup suspended the participants for less than 30 seconds. The quantity and quality results for the generated ideas revealed that this interruption had no effect on the idea generation, so the results from the team are deemed valid.

3.1.5 Controlled study participants

The participants are students in the second semester of the capstone design sequence. Students work in the same teams they worked in during the previous semester. Eight teams are recruited. Participants have to sign up in the team to which they are assigned in the design class. All tested teams have three members.

The average age of the participants is 22.45 years, ranging from 21 to 26 years. All participants are male. Seventeen participants had industrial experience (including internships); 16 of them worked full time for periods between 3 and 24 months, with an average of 7.8 months. One participant had seen a television program on industrial solutions to the experiment's design problem.

Instead of doing a count of the unique ideas per team member, the average number of ideas per team member is calculated by identifying how many ideas each team member contributed. The data was recorded between exchanges so that the number of ideas contributed by each team member could be easily identified. The analysis at the individual member level provides a larger sample size resulting in greater statistical significance.

3.2 Capstone study

The Capstone Study involved three teams of students enrolled in the first semester of Texas A&M's mechanical engineering capstone design course. One team was collocated, all at TAMU-CS, while the other two teams were distributed with members divided between TAMU-CS and TAMU-Qatar. Two of these design teams worked independently on a project sponsored by FMC Technologies while the third team's project was sponsored by the Shafallah Center for Children with Disabilities.

The FMC project was to design a 'rigless abandonment tool' for deep-sea oil wells. This tool is to mate with and actuate existing machinery on an abandoned underwater rig to allow a large part of the well head to be removed and recovered. Students working on the Shafallah project were asked to design a wheelchair simulator to help teach children to safely and effectively operate a powered wheelchair.

3.2.1 Capstone study research question

When examining the ideation process for the capstone design teams, the most significant difference from conventional idea generation methods is the separation of the team members. Thus, the experiment is designed to help answer the question of whether a design team's distribution influences solutions generated using the modified 635 method.

3.2.2 Capstone study experimental design

Three design teams took part in this experiment, with team members enrolled at TAMU-CS and TAMU-Qatar. The class consists of three teams; two of them are distributed teams with team members on both campuses. Team one had five team members, three in College Station and two in Qatar. Team two has four team members, two at each location. Team three has three team members, all in College Station.

The experiment is a between-subjects one-factor study, with independent variable of team distribution. The dependent variable is the quantity of non-redundant ideas per team. This experiment has only two conditions. In both conditions, ideas are generated using the modified 635 method with a time delay, but one condition uses a collocated team while the other uses a distributed team. The team members of the distributed teams that were at one location were in one room and were able to see each other during the experiment.

3.2.3 Capstone study participants

All the participants are senior-level engineering undergraduates and two are female. The experiment took place during the sixth week of classes.

3.2.4 Capstone study experimental materials and procedure

The students use pens and paper to develop and record their ideas. Their papers are later scanned and emailed to the other campus. To ensure that all students received the same instructions, a videoconference system is used to instruct the students in Qatar, and a professor in Qatar assists with the procedure.

Because team one is larger than team two, directly comparing the ideas each team generates is difficult. To simplify the analysis, the ideas generated by one member, selected at random, from team one's College Station students are not included in this study.

3.3 Experimental metrics

In the modified 635 method conditions, a complete solution to a design problem refers to one sketch and its annotations. In the brainstorming conditions, a complete solution is either the content of the note page or, if the team clearly indicated segments, one segment of the page. All solutions of a team are a 'set of solutions' or the 'team's solutions'. A solution can consist of multiple ideas, for example a conveyor belt may consist of the ideas belt, stands, and guide rollers. While the ideas generated in the Capstone Study were evaluated only qualitatively, the data from the Controlled Study is evaluated using four metrics: quantity, quality, novelty and variety.

3.3.1 Capstone study quantity metrics

The quantity measure is used to compare the effectiveness of each idea generation processes. Building from the work of Shah et al. [42] and implemented in by Linsey et al. [43], the basic definition of a single 'idea' is something that fulfills at least one function of the functional basis as described in Stone and Wood [44]. The quantity of non-redundant ideas for the team is determined by counting each idea only once for the whole team, so if three team members independently generate the idea of using a scale, the scale is counted as one unique idea for the team. The guidelines for this metric are summarized in Table 1.

3.3.2 Controlled study quantity metric

The approach used to evaluate the quantity of the generated ideas per team is based on the counting technique used by Linsey et al. [41, 43] as presented in the capstone design study quantity metrics section. Experience in the previous study suggested some addenda to the counting rules.

Firstly, as brainstorming conditions not only produce a list of keywords but often also contain sketches, consequently, any identifiable discrete components in sketches produced during brainstorming are counted as ideas. Secondly, because the tablet screens allow erasing of sketched compo-

Table 1. Summary of Quantity Metric Rules [43]

1. An idea solves one or more of the functions in the functional basis (primary or secondary function).
2. The same idea (or component) being used in multiple places counts as one idea. Redundant ideas are only counted once.
3. Each idea counts as only a single idea even if it solves more than one function. A single component such as a motor can solve more than one function such as producing heat and increasing torque.
4. New combinations of already-counted ideas are counted in a separate measure as one new idea.
5. Categories of ideas only count as ideas when no subordinates are given, for example gear is one, but gear, helical gear, and planet gear are only two ideas not three.
6. Ideas count even if they are not needed or cause the systems to not function.
7. Ideas must be shown and not just implied.
8. For ideas that reframe the problem such as producing a slightly different product or ways to reduce waste product, count these in a category called 'Problem Reframing.' These are ideas that do not specifically address the problem as describe but meet the higher level customer needs.
   a. Ideas that reframe the problem usually do not fit a defined product function well.
   b. They must add something to the system.
   c. Count them if they are related to the situation such as:
      i. Environmental concerns relate to the situation.
      ii. Reduction in waste products resulting from solutions to the problem.
      iii. Produces a different product that meets the customer needs.

nents, and because the voice recordings allow capturing all verbally expressed ideas, any erased ideas or ideas that were verbally communicated, but unwritten, are counted.

The approach to evaluating the ideas per team member matches the approach described by Linsey et al. [41, 43]. If team members have the same idea during the same time period, they share the credit for it and fractional counts are used. Further, if an idea occurs during an earlier idea generation cycle, no points are awarded for it again, even if the person had not had a chance to see this idea. This means if participant X is the only participant who sketches a lever during the initial idea generation, no other participant will receive credit for a lever in a later cycle, even if they have not seen participant X's sheet.

3.3.3 Controlled study quality metric

The quality of this study's generated ideas is measured using used an anchored three point rating scale developed by Linsey et al. [41]. The quality rating scale, depicted in Fig. 2, first asks if the idea is technically feasible. If it is not, zero points are awarded and the rater proceeds to the next idea. If the idea is feasible, then the next question is: Is the idea technically difficult for the context? If it is, one point is awarded. If the idea is not technically difficult, two points are awarded. The rater then moves on to the next idea. All sketched components and words that have been identified as ideas during the quantity counts are evaluated for quality. This rating scale is suitable for a wide range of design problems. Depending on the specific design problem, the presented three point rating scale can be refined by adding more questions and expanding the point range. The quality rating of an idea is independent of other ideas, and thus can be evaluated while the series of experiments is in progress.

3.3.4 Controlled study variety and novelty metric considerations

Novelty reflects how unusual or unique a solution is in comparison to the other generated solutions. Variety shows how diverse the team's solutions are, or how much of the solution space spanned by all solutions generated by all teams is covered by one team's solutions. The method used to evaluate the experiments at hand is presented in Linsey, et al. [41]. Novelty and variety are evaluated on the idea level, not on the solution level. Each generated idea is separated onto a single page. These pages are given to an independent rater, who sorts the solutions into groups of similar ideas. Each rater constitutes for himself what similar means in the rating.

3.3.5 Controlled study variety metric

The variety of a team's ideas is the solution space spanned by the ideas. The variety of one team's ideas is defined as the number of groups that the team's ideas are sorted into. Each evaluator is told to put similar ideas together and told an approximately number of categories. The evaluator determines what constitutes similar. Inter-rater agreement then verifies that the measure is reliable. For example, if a rater creates 25 groups and one team's ideas are found in five of those groups, the team's variety score is 5/25 = 0.2 or 20%. The team's ideas span 20% of the solution space created by all ideas of all teams who participated in the experiment.

3.3.6 Controlled study novelty metric

The novelty metric measures the frequency of the occurrence of the idea based on the evaluator groups discussed in the variety metric section. For one idea, it is measured by subtracting the number of concepts in a group divided by the number of concepts generated by all teams. For example, if a rater places an idea in a group that contains 5 ideas, and all teams produced a total of 200 ideas, then the idea's novelty score equals 1–5/200=1–0.025=0.975. The Novelty score of all of a team's ideas is calculated by averaging the novelty scores of the team's ideas.

3.3.7 Rater training procedure

Three raters were trained to assign scores to each generated idea using the four metrics that have been introduced. The raters were each presented with a set of the metric rules and used them to rate ideas from the data set presented by Linsey et al. [43]. All the raters possess a background in engineering

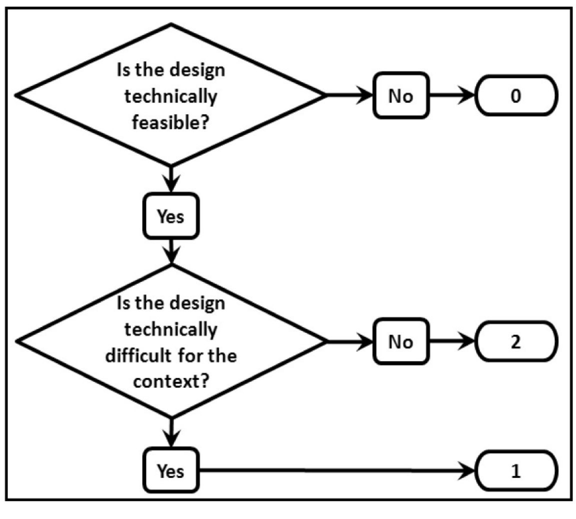

Fig. 2. Three point rating scale for quality rating in the Controlled Study.

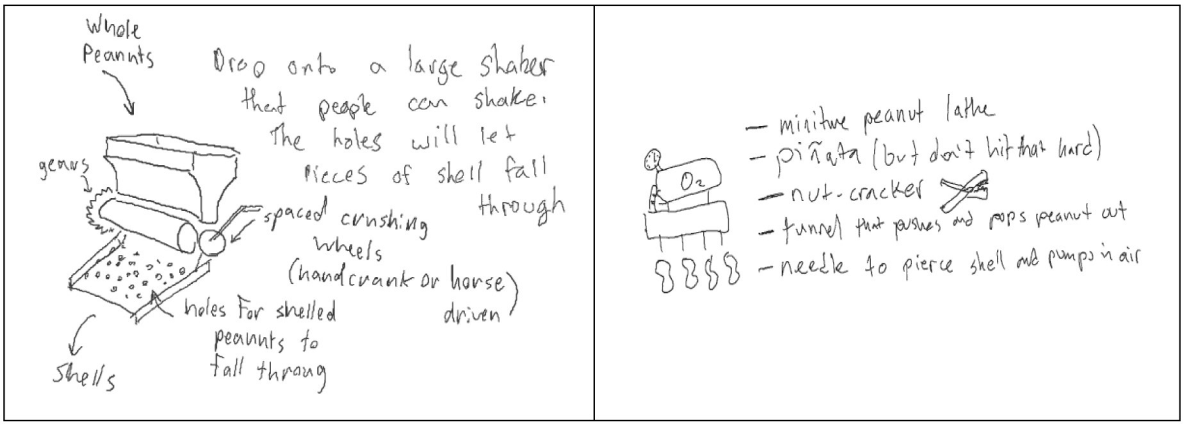

Fig. 3. Selected solutions from the Controlled Study. Left: modified 635 method; Right: brainstorming.

design and found no difficulty in applying the metrics.

4. Results and discussion

We begin by presenting and discussing the results from the Controlled Study. Afterwards, we discuss the results of the Capstone Study and compare them to the Controlled Study's findings.

4.1 Controlled study

The brainstorming teams generally use keywords to capture their ideas and sometimes add small sketches to illustrate a specific point. The brainstorming teams are neither encouraged nor discouraged to sketch during their instructions. The modified 635 method teams are told to sketch and explain ambiguities with keywords or short phrases. Figure 3 shows a typical solution to the peanut shelling design problem produced by each ideation method. The left portion shows a result produced using the modified 635 method and right using brainstorming.

Solutions including how to import the peanuts, how to shell them, and how to separate the nut from the shell are common in the modified 635 method. In brainstorming it is more common to find keywords without further explanations describing some function or an analogous product, such as 'cotton gin.'

4.1.1 Controlled study quantity results

A summary of the results per condition is given in Fig. 4. This graph shows the average number of non-redundant ideas each team member produced. This average is not the total quantity of ideas produced by the two teams working on each condition divided by the six team members, but rather the average of the number of non-redundant ideas each *individual* produced, measured as described in section 3.3.2. The biggest variation in the quantity of ideas per team can be seen in the brainstorming distributed condition, with one team generating 40, and other only 20 ideas. The inter-rater agreement (Pearson's Correlation) is 0.85 for the unique ideas per team member and 0.66 for the ideas per team counts.

Trends across the number of ideas per individual and per team are similar, but the analysis done on a per individual basis results in higher statistical significance due to the sample size. A count per team member takes the individual abilities of the participants into account. Using the individual counts triples the number of data points available in the team counts giving a total sample size of 24 data points. An ANOVA analysis with the 24 data points representing the quantity of ideas per team member and condition shows a significant influence of the idea generation method on the number of ideas generated per team member. The results of this analysis are detailed in Table 2 and presented in a standard ANOVA table format with SS (Sum of Squares), df (degrees of freedom), F ratio, and p (probability based on the F ratio) indicated. The ANOVA results indicate that the number of ideas generated is only dependent on the idea generation method used, not on the location of the team and is there is not any interaction between these factors. This is indicated by the probability (p) being less

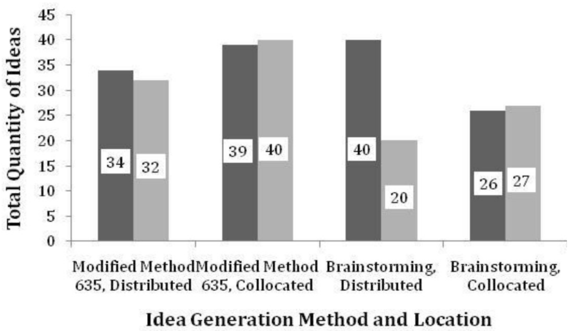

Fig. 4. Controlled Study: total number of non-redundant ideas produced by each team.

Table 2. Controlled Study: quantity of ideas per team member ANOVA results

Source	SS	df	F	P
Location	1.00	1	0.08	0.78
Idea Generation Method	57.35	1	4.40	0.05
Location × Idea Generation Method	4.95	1	0.397	0.54
Error	259.66	20	(12.98)	

Note. Value enclosed in parenthesis represents mean square error.

than 0.05 for the factor of idea generation method and greater than 0.05 for the location and interaction (Location X Idea Generation Method). For distributed teams, this implies that the lack of face-to-face meetings and electronic communications—as used in the experiment—has no effect on the number of ideas they generate. This result is positive in the sense that distributed teams can have as many ideas available for the future phases of the product development process as collocated teams. This contrasts prior literature that states that distributed teams face additional challenges in phases of the design process that collocated teams do not.

4.1.2 Controlled study quality results

All ideas are evaluated for quality following the three-point rating scale discussed in the section 3.3.3. The average quality scores per team and condition are summarized in Fig. 5. The average quality value over all teams is 1.52, with each team's value using the modified 635 method quality being above or about this value, and all team's quality values using brainstorming being below this value.

An ANOVA analysis reveals a significant dependence of the quality of a team's ideas at the $p<0.1$ level for both factors examined, but not their interaction. Table 3 presents the results of the ANOVA. This statistical analysis indicates that both the team distribution and the idea generation method have a significant influence on the quality of a team's solutions.

Overall, teams using the modified 635 method in a distributed setting produce the highest quality ideas. Teams using the collocated modified 635 method produce the second highest quality ideas. Third are the distributed brainstorming teams, with the lowest quality ideas generated by collocated brainstorming teams. A graphical representation of these results is presented in Fig. 6.

A comparison of the distribution of quality scores across conditions is shown in Fig. 7. The data shown in Fig. 7 suggest that the number of feasible and appropriate ideas, for which two points are awarded, increases when using modified 635 method conditions. In the modified 635 method, teams produce a higher number of ideas as each component or method sketched or written down is evaluated separately. For example, a table consists

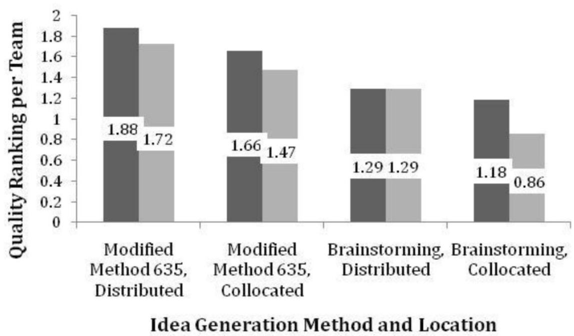

Fig. 5. Controlled Study: quality rankings per team per condition.

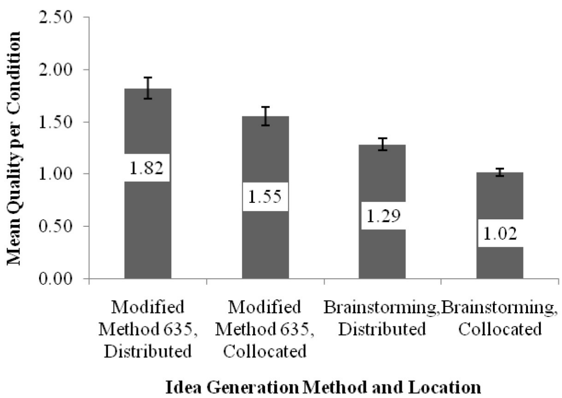

Fig. 6. Controlled Study. 1st rater mean quality per condition (±1 SE).

Table 3. Controlled Study: ANOVA quality results

Source	SS	df	F	P
Location	0.127	1	6.22	0.07
Idea Generation Method	0.557	1	27.13	0.01
Location × Idea Generation Method	0.001	1	0.03	0.87
Error	0.082	4	(0.02)	

Note. Value enclosed in parenthesis represents mean square error.

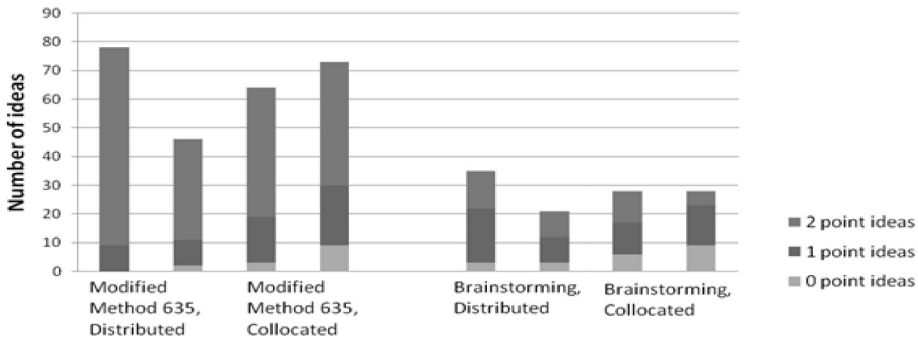

Fig. 7. Controlled Study: number of quality ideas per team.

of a tabletop and legs, both of which are rated separately for quality. Furthermore, not only are unique ideas evaluated for quality—if a second table is drawn, it is evaluated in the same way as the first one.

The percentage of infeasible ideas is very small in the modified 635 method distributed condition—far less than 5% of all ideas. The first collocated brainstorming condition has the highest percentage of infeasible solutions, slightly more than 25%. The modified 635 method collocated and the distributed brainstorming conditions both have around 10% of infeasible ideas. The brainstorming conditions have between 45 and 50% of feasible, but unsuitable, ideas for the context, for which one point is awarded. These ideas are more prevalent in brainstorming than in the modified method 635 method conditions with 15 and 25%. Unsuitable ideas can still contribute to a product development project through inspiring another idea. Nevertheless, these unsuitable ideas are not evaluated here.

The distributed 635 teams have the highest percentage of solutions that work in the context of the design problem, about 65 and 80% compared to slightly less than 30 or 40% in the brainstorming conditions.

4.1.3 Controlled study novelty and variety inter-rater agreement

Two raters sorted the solutions of the eight teams to allow the calculation of novelty and variety. The 373 ideas were sorted into 75 bins by the first rater and into 78 bins by the second rater. The inter-rater agreement is calculated using (Pearson's Correlation) and is large, with PC=0.9. The level of correlation allows the use of only the 1st rater's evaluation data in the analysis, as only minor changes are expected when using the data of the second rater or the average of both raters.

4.1.4 Controlled study novelty results

Performing an ANOVA analysis on the assigned novelty values shows that both factors have a significant main effect. Table 4 presents the results of this analysis.

Table 4. Controlled Study: ANOVA novelty results, 1st rater.

Source	df	F	P
Location	1	26.18	0.01
Idea Generation Method	1	52.55	0.00
Location × Idea Generation Method	1	1.64	0.27
Error	4	(0.00)	

Note. Value enclosed in parenthesis represents mean square error.

According to these results, the ideas generated by collocated teams are significantly more novel than the ideas generated by distributed teams, independent of the idea generation method employed. Additionally, teams using brainstorming produce significantly more novel ideas than teams using the modified 635 method, independent of the location of the team members.

Figure 8 shows that the collocated brainstorming teams generate the most novel ideas, followed by distributed brainstorming teams. The third most novel ideas were produced by the collocated modified 635 method teams, while the distributed modified 635 method produced the smallest number of novel ideas. The information in

Figure 8 is produced from the mean novelty scores of each team in a manner identical to that described in the discussion of Fig. 4.

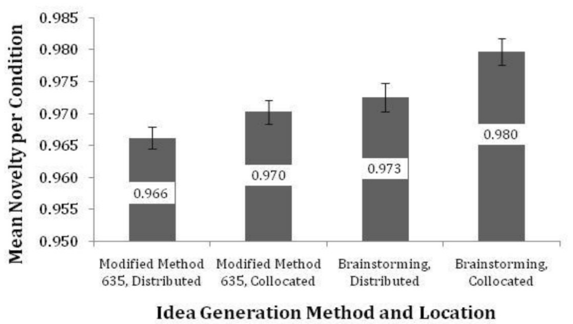

Fig. 8. Controlled Study: 1st rater novelty mean values per condition (±1 SE).

4.1.5 Controlled study variety results

Using the variety values of the first rater in the ANOVA analysis, both factors have a significant main effect, as seen in Table 5.

Collocated teams produce ideas with a significantly greater variety than distributed teams independent of the used idea generation method. Additionally, teams using the modified 635 method generate significantly more varied ideas than teams using brainstorming, independently of the location of the team. Figure 9 clearly shows that the teams using the modified 635 method in a collocated setting generate ideas with the greatest variety. The second biggest variety is achieved by the teams using the distributed modified 635 method. The teams using brainstorming produce the least varied ideas, with the collocated teams generating a greater variety than the distributed teams.

4.2 Capstone study

The formal idea generation analysis in section 4.1 shows that distributed and collocated teams perform differently in concept generation exercises. However, over the course of the capstone design projects, informal qualitative feedback from the students indicates that the distributed nature of the teams introduced minimal disruptions in the design process. Despite the large spatial and temporal separation between the members of the FMC and Shafallah design teams, the students quickly adapted to their distributed status and established regular communication amongst themselves. The instructors did not have to actively work to ensure communication between the students in College Station and Qatar.

After an initial team video-conference, the abandonment tool team opted to communicate through email and Skype based communication. The majority of this team's communication was asynchronous; they rarely found a need to communicate in real-time. The wheelchair simulator team also adopted email and Skype based communication, but decided to schedule a weekly video-conference as well. The instructors observed that both teams were communicating equally effectively, irrespective of their communication structure.

The instructors observed no significant differences between the communication efforts of the distributed design teams and those of traditional collocated teams they had worked with in the past. Although the teams had to contend with the occasional failures of internet communication— full inboxes, corrupted attachment, etc. —these problems were no more severe than those typically experienced by collocated teams. In short, the design teams' global distribution did not noticeably impair team communications.

Many concepts and methods taught in the capstone design course lecture are centered around the concept of the team. Indeed, many methods rely on real-time interaction between team members. For example, Osborn's formal brainstorming method requires synchronous verbal communication between all the team members [29]. The nine time zones lying between the members of the abandonment tool and wheelchair simulator teams precluded the level of real time interaction that a collocated team enjoys. This separation presented an opportunity to study how non-verbal idea generation methods can be adapted for distributed design applications.

Both design teams used a modified 635 method to generate ideas for their project. In this method, each team member sketches and annotates three ideas on a sheet of paper. After fifteen minutes, the sheets are passed around the table and the next person adds new ideas to the sheet for an 8 minute period. The sheets are exchanged until each sheet has been seen and modified by each person. Originally, this method was developed for a group of six people, but it can be adjusted to accommodate teams of any size.

The large time difference precluded conducting this exercise in a single sitting. Students at each location performed one exchange, and then the

Table 5. Controlled Study: ANOVA variety results, 1st rater

Source	df	F	P
Location	1	10.18	0.03
Idea Generation Method	1	17.28	0.01
Location × Idea Generation Method	1	3.37	0.14
Error	4	(0.00)	

Note. Value enclosed in parenthesis represents mean square error.

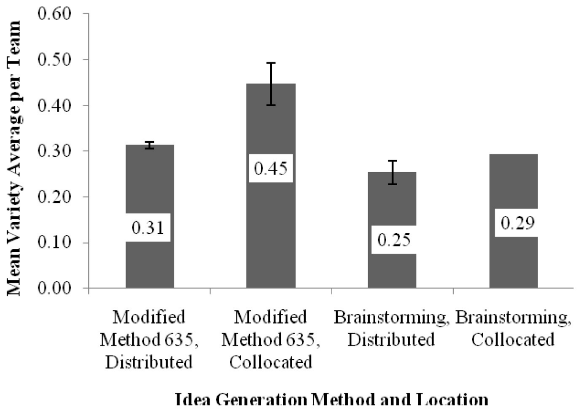

Fig. 9. Controlled Study: 1st rater variety mean values per condition (±1 SE).

Table 6. Capstone design: number of unique ideas per team

	Wheelchair Simulator	Abandonment Tool
Distributed	25 (4)	32 (4)
Collocated	—	33 (3)

papers were scanned and emailed so the students at the other location could complete the exercise the following day. As a control group, a second, collocated, team working on the abandonment tool project also took part in this exercise, complete with the overnight gestation period.

One of the teams had five members; the ideas produced by one randomly selected member in the College Station portion of this team are not counted in this study. Discarding these ideas allows the output of two four-member teams to be compared rather than attempting to normalize the results for the team size.

The ideas generated by each team are counted using the procedure outlined in the metrics section. The number of unique ideas per team and the number of team members on each team are given in Table 6. The number of team members on each team is noted in parentheses.

The collocated abandonment tool team produced only one more unique idea than the distributed team. However, the distributed teams had the advantage of an additional member. Thus, the average number of unique ideas *per team member* was higher for the collocated team. Unfortunately, the small sample size of this experiment precludes any accurate statistical analysis, and it is impossible to compare the number of ideas produced for the abandonment tool project with those for the wheelchair simulator project because of the fundamentally different design problems. Thus, any conclusions we reach are strictly qualitative. Nevertheless, this study clearly establishes that the modified 635 method is a suitable idea generation method for distributed design applications. Furthermore, the number of unique ideas produced by the abandonment tool teams are comparable, and seem to validate the Controlled Study's finding that the number of ideas produced is independent of the team's distribution.

5. Summary and conclusions

Engineering is becoming an increasingly global activity, with project teams composed of members scattered around the globe [1]. However, despite the globalization of engineering practice, engineering education remains regional in nature [3]. Even when engineering classes may contain students from a plethora of geographic and cultural backgrounds, the students still live and work in a single region and on a relatively common schedule. Certainly, collocating students offers logistical advantages when teaching them the fundamentals of engineering in a classroom. However, courses that seek to help student transition from the classroom to the workplace, such as capstone engineering design courses, ought to reflect the globalization seen in engineering practice.

Integrating distributed design into the capstone design experience poses some pedagogical challenges. Many traditional engineering design techniques taught to students are designed for collocated teams and are taught as such. Idea generation techniques are particularly problematic because some, such as brainstorming, use group dynamics to promote creativity. To address this problem, we have examined two studies to gain insight into the effect a design team's distribution has on the ideas they produce.

The Controlled Study is designed to determine how the ideation method used and the team's location distribution influence the ideas a design team generates. Teams use either brainstorming or a modified 635 method to generate ideas in either collocated or distributed configurations. The teams that participated in the study were design teams enrolled in the second semester of Texas A&M's mechanical engineering capstone design course. The ideas generated in this study are evaluated in terms of quantity, quality, novelty, and variety. Teams using the modified 635 method generate the highest quantity of ideas, regardless of the team's distribution. The highest quality ideas are produced by distributed teams using the modified 635 method. Collocated brainstorming promotes the most novel ideas, while the collocated modified 635 method generates the greatest variety.

The ideation experiment conducted with the globally distributed capstone design teams allow the results of the Controlled Study to be tested in a very realistic distributed design setting. Despite the large spatial, temporal, and even cultural barriers between the members of the design teams, the students quickly established regular and reliable communications and performed as well as typical collocated design teams. The capstone study confirms that the modified 635 method is a viable idea generation technique for distributed teams. Comparing the number of ideas produced by the two abandonment tool teams suggests that the number of ideas produced with the modified 635 method is independent of the team's distribution, agreeing with the results of the Controlled Study. However, the small sample size in the capstone study experiment makes this last conclusion tentative at best.

These results indicate that teams working in distributed settings should use a combination of group idea generation methods to maximize the novelty, quantity and variety of ideas. Based on the results, student teams should be taught to first use 635 to generate a variety of high quality ideas. They then should brainstorming to generate novel ideas and then another round of 635 to enhance the quality of ideas. Engineering design team should also select idea generation methods based on the needs of the project. If teams need very novel solutions, brainstorming is a good choice. If a team instead needs to increase the variety of ideas under consideration or the quality, then 635 is an effective choice.

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