Research in Engineering Design
https://doi.org/10.1007/s00163-018-00303-3

ORIGINAL PAPER

Are you better off alone? Mitigating the underperformance of engineering teams during conceptual design through adaptive process management

Joshua T. Gyory[1] · Jonathan Cagan[1] · Kenneth Kotovsky[2]

Received: 11 April 2018 / Revised: 13 November 2018 / Accepted: 14 November 2018

Abstract

Teams are a major feature of engineering and are commonly thought to be necessary when solving dynamic and complex problems. Even though teams collectively provide a diversity of knowledge, skills, and perspectives to problem-solving, previous work has demonstrated that in certain scenarios, such as in language-based and more spatially oriented configuration design problems, the production by a team is inferior to that of a similar number of individuals working independently (i.e., nominal team). This research explores this comparison of individual versus group problem-solving within the domain of conceptual engineering design. Thus, a behavioral study was run with freshman engineering students, who solved a conceptual engineering design problem individually or collaboratively in a team. Results corroborate previous findings, exhibiting that individuals outperform teams in the overall quality of their design solutions, even within this more free-flowing and explorative setting of conceptual design. Exploiting this result, this work further considers whether adaptive feedback from a process manager can lessen the underperformance of collaborative design teams compared to individuals, by helping teams overcome potential deterrents that may be contributing to their inferior performance. Teams that are under the guidance of a process manager end up performing better than teams that are not in terms of solution quality, and almost as well as individuals, though not significantly different. This result suggests that process managers are able to mitigate some of the deficiencies in design teams. In an attempt to uncover some of the cognitive rationale and strategies that may be beneficial throughout problem-solving, the managerial interactions with the design teams are then investigated. Furthermore, to determine the reason of the collaborative teams' underperformance, the effect of verbalization is studied as a possible cognitive hindrance. In the end, this work expands growing research on team problem-solving in engineering, and suggests that collaborative teams may not be optimal in every circumstance, but under the proper process management, can become substantially more effective.

Keywords Engineering design · Teams · Conceptual design · Process management

1 Introduction and background

1.1 Teams in engineering

Teamwork pervades the modern practice of engineering, both in academia and industry (Bellamy 1994). Providing a diversity of knowledge and perspectives, team problem-solving is particularly crucial when the given task may be too challenging or complex for individual expertise and effort. For effective problem-solving, team members must be able to collaborate and communicate with one another (Hoffman 1965; Laughlin 2011). Beginning in the early stages of their careers, engineers are trained via problem- and project-based experiences to provide them with these

✉ Jonathan Cagan
cagan@cmu.edu

Joshua T. Gyory
jgyory@andrew.cmu.edu

Kenneth Kotovsky
kotovsky@cmu.edu

[1] Department of Mechanical Engineering, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

[2] Department of Psychology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

Published online: 29 November 2018

hands-on, team-oriented skills to prepare them for the rigors and demands of engineering design in practice (Dutson et al. 1997; Seat and Lord 1999; Mills and Treagust 2003). Sharpening these collaborative techniques can improve upon the competencies of making decisions, exchanging technical ideas, and resolving conflicts, to help abate any dissension that may arise within the team (Turkalj et al. 2008; Tesluk et al. 2009). Effective communication strategies can also lead to a common, shared mental model of the problem among team members, fostering team synergy and improving the collective team performance (Dong et al. 2004; Kim 2007).

1.2 Drawbacks to teams

Although there are numerous benefits to teams, there also exist some generally acknowledged deficiencies (Maier 1967). Social loafing, for example, is a psychological phenomenon in which individuals tend to expend less effort when working in a group, as opposed to working individually, even to the extent of withholding information from the rest of their group members (Karau and Williams 1993; Alnuaimi et al. 2010). This is due to the belief that an individual's work (or lack thereof) will be obscured relative to the efforts by the rest of the team. Furthermore, group think is a psychological drive for a consensus among a group in an attempt to avoid any potential confrontations or disagreements. This phenomenon may lead to a premature decision, even on one that some members may not agree with, and in turn, can hinder creative thinking (Janis 1972; Schmidt 2013). A dominant individual can also emerge from the group, who pressures other team members, and consequently, has an unduly greater share of impact on the final outcome of the team, often resulting in more polarized decisions (Myers 1976). This influence may not necessarily stem from a higher degree of knowledge or problem-solving ability, but from that individual simply being more persuasive and resolute. Thus, many of these deficiencies in teams have to do with the problem-solving process itself, as opposed to individual experience or knowledge. Perhaps, as Maier put it, there is a "need for an integration function" that could mitigate some of these process shortcomings in groups by acting as their central nervous system (Maier 1967).

Previous work in psychology and configuration engineering design has supported this assertion that teams may not always be maximally proficient (Faure 2004; Rietzschel et al. 2006; Putman and Paulus 2009). Many of these studies utilize the term *nominal team* to refer to a team of participants who work individually, but whose efforts are pooled together with the best solution chosen to form the collective team performance. Nominal teams are necessary in these studies to be able to make comparisons between individuals and interacting teams. In brainstorming studies, interacting groups are shown to generate fewer ideas than nominal brainstorming teams (Taylor et al. 1958; Diehl and Stroebe 1987). In language-based, Remote Associate Test (RAT) puzzles, interacting groups perform worse than non-interacting nominal groups (Sio et al. 2018). Remote Associate Tests are word-retrieval protocols which measure analytical and convergent thinking ability (Lee et al. 2014). The test is done by having the participant form compound words/phrases through a given set of provided cue words by finding the common term that links with all three cues. It is inherently a language-based task because of this dependence on semantically related word retrievals. Additionally, in configuration engineering design problems, McComb et al. behaviorally studied and computationally simulated human design teams. Configuration design refers to a subset of design problems that involve pre-defined set of components that can be combined based on interface constraints and requirements of the task (Mittal and Frayman 1989). In their work, they showed that under certain problem characteristics, such as objective alignment and global structure, zero interaction frequency among team members resulted in optimal performance (McComb et al. 2017). This zero interaction frequency finding indicates that individuals, i.e., nominal teams, would be the preferred structure under these circumstances.

1.3 Overcoming a drawback: impasses in creative and conceptual design

The current work exploits previous findings of individual and team performance but on a different type of design problem, conceptual engineering design. Conceptual design is free flowing and exploratory in the early stages as with brainstorming, but narrows down to seek high quality and practical solutions. It is also structured and constrained as with configuration design, but while conceptual design is open-ended, configuration design is limited to the combinatorics of a finite set of enumerated components. Thus, because configuration design problems utilize these predefined components to work with, there is normally a single best assembly/solution (Wielinga and Schreiber 1997). Conceptual design is initially more open-ended, in that there could be multiple preferred solutions that satisfy the problem, although a single concept must be selected by the end amongst these design alternatives. Moreover, unlike previous brainstorming studies, this work presents an engineering design problem that more accurately emulates one that would be encountered in practice, with dynamically changing design constraints (Liu and Boyle 2009). Thus, this work seeks to understand how teams behave in this early, albeit critical, part of the engineering design process.

Engineering teams may often reach impasses during problem-solving (McComb et al. 2015a), as do people solving RAT problems (Moss et al. 2011). Additional aid in the form of analogies and solution examples has been shown to stimulate group creativity and improve solution quality, particularity during brainstorming tasks and the ideation stage of conceptual engineering design (Fu et al. 2010; Linsey et al. 2012). However, such aid can also lead to fixation, which is a blind adherence to a set of ideas or concepts. Fixation can suppress team creativity and lead to inferior overall performance (Jansson and Smith 1991; Sio et al. 2015). Work on creativity tasks has tried to lessen this fixation effect, for example, through providing expansive versus restrictive examples (Agogué et al. 2014), effectively managing non-verbal devices such as pictures or sketches (Brun et al. 2015), as well as examining the specificity and level of abstraction of such (Ezzat et al. 2018). Furthermore, theoretical models have been developed for leadership strategies in creativity tasks (Rickards and Moger 2002). Perhaps some of the aforementioned deficiencies in team problem-solving can be ameliorated in conceptual design if a portion of the resources used for solving the problem are instead used to guide and control the team's design process. This work considers allocating these resources to a human manager, who acts as a team's central processing system, to gather feedback and provide adaptive management. Previous work on design creativity provides stimuli to problem-solvers that are static in nature, such as in constant modalities and/or at pre-defined intervals. The integrative role of the process manager in this current work provides real-time feedback to design teams that is fluid in both modality and timing, adapting to a team's current state and how they evolve throughout the problem-solving process.

1.4 Research goals

Consequently, this research is motivated by two goals. The first seeks to determine whether the underperformance of team problem-solving, identified in language-based and configuration design, applies to the conceptual phase of design, by comparing individual and team performance in this domain. The second goal is to explore whether a portion of the resources used for problem-solving could instead be used to dynamically manage and control the design process of the remainder of the team and improve performance via a human manager. The effect of the process manager on design teams is studied and the performance compared to that of both unmanaged and nominal teams. After this comparison, an amalgamative analysis, with both quantitative and qualitative features, is done to uncover some of the managerial strategies, and the rationale behind which, are most beneficial to design teams.

To form a conceptual framework, this paper begins by introducing the experimental architecture and logistics of the behavioral study that is run to answer the aforementioned research goals. Here, three different types of team conditions will be defined, for consistency, and used throughout the remainder of the paper: a managed team (problem-solvers who work together and are overseen by a more experienced process manager), an unmanaged team (problem-solvers who work together and are not overseen by a more experienced process manager), and a nominal team (individual problem-solvers who do not work together but are randomly placed together to form an artificial team). Also in this section is a description of how the process managers are chosen and the methods by which they are able to intervene with their design teams. The next sections provide an overview of the analysis metrics and techniques that are used to compare problem-solving performance (design quality, design novelty, and team cohesion), followed by the presentation of the results and the process manager interventions. The paper concludes with a discussion of the strategies and cognitive rationale of the process managers, as well as a supplemental experiment studying the effect of verbalization. As the primary means of conveying ideas, teams are required to communicate and verbalize with each other, which is one of the main differences between individual and team problem-solving. Also motivated by previous research studying this effect, whether verbalization acts as a cognitive deterrent during conceptual engineering design problem-solving is examined. Finally, limitations of the study and future work are acknowledged, followed by brief remarks on the implications of this work for engineering design teams and design practice.

2 Methodology

2.1 Experimental conditions

To address these two primary research goals, a behavioral study was run with freshman engineering students at Carnegie Mellon University in Pittsburgh, PA, USA. Participants for the study were recruited from the "*Fundamentals of Mechanical Engineering*" class, a freshman-level course in the Mechanical Engineering department. The intention was to recruit students with comparable and little to no prior exposure to techniques and theories in engineering design methods and conceptualization. In total, 95 freshman engineering students participated in the study. Because students were recruited through their engineering course and participated in the study in lieu of a scheduled lecture, they were not monetarily compensated for participating. However, during the time period they were not participating in the study, they received an educational lecture on engineering ethics.

These students, or novice designers, were randomly assigned to one of three different team conditions: a managed team, an unmanaged team, or a nominal team (see

Fig. 1). A managed team was composed of four freshman engineering students collectively solving the problem, with one mechanical engineering graduate student as a manager overseeing their design process. An unmanaged team was comprised of five freshman engineering students and no graduate student manager. The additional problem-solver in the unmanaged teams was to keep the number of personnel equivalent across the two experimental conditions. Lastly, a nominal team was composed of five randomly chosen freshman engineering students (of the 23 participants) who solved the problem individually but did not interact with each other. Instead, the best solution was chosen from amongst the five individual solutions. In total, there were eight managed and eight unmanaged teams, and 23 individuals from which eight nominal teams were artificially created to compare with the other team conditions. The method for generating the nominal teams will be discussed later in the paper.

2.2 Process manager selection and manager bank creation

The managed teams were composed of four freshman novice designers and one graduate student process manager. These managers were able to intervene with their team to affect the solving process with different stimuli, but could not directly contribute to the problem solution. The graduate students were selected for the study via a recruitment survey that was disseminated to a portion of the graduate student population in the Mechanical Engineering Department at Carnegie Mellon University. The response rate from the surveys was 68%, with 40 graduate students completing it.

The desired managerial characteristics were the possession of engineering design knowledge and prior experience in leading a team. Using a Likert scale assessment, questions on the survey queried the graduate students to self-assess their mechanical engineering design knowledge, as well as their leadership experience. To minimize survey bias due to over- (or under-) confidence in their own abilities, supplemental questions asked them for specifics such as undergraduate/graduate classes they had taken in engineering design, the area of their primary research, areas of interest outside of their primary research, and specific examples they had in leading a team. The eight graduate students with the highest level of design knowledge and leadership experience were selected as the process managers for the study.

Even though the managers were instructed to intervene when they felt it necessary, they were only allowed to interact with items from a bank of prescribed stimuli. Three distinct categories of interventions were chosen, theoretically grounded in previous literature for different modalities and stimuli for improving ideation and problem-solving effectiveness. Inspired by the approaches of design by analogy and metaphor, *keywords* were selected, a technique known to help designers divergently think about and reframe the problem in a different domain (Hey et al. 2008; Goucher-Lambert et al. 2018). Cognitive priming with solution examples, shown to increase quality output (Fu et al. 2010), inspired the use of different *design components*. Moreover, because visual representations have been shown to be a more effective modality (Goldschmidt and Casakin 1999), these components were pictorially depicted. Heuristics for creative problem-solving and management (Yilmaz and Seifert 2010; Isaksen 2013) influenced the use of *design strategies,* where designers with more structured planning and approach perform better. Thus, previous literature motivated the following intervention types that were, respectively, chosen: *keywords, design components*, and *design strategies*.

The collection of permissible stimuli was created for this particular problem from questions in the manager recruitment survey. In the survey, each potential manager was asked to generate possible items in each of those categories that they might provide to a hypothetical engineering team to aid in solving the design problem used in the study. After the graduate students with the highest level of engineering design knowledge and leadership experience were chosen through the survey, their answers to these questions were

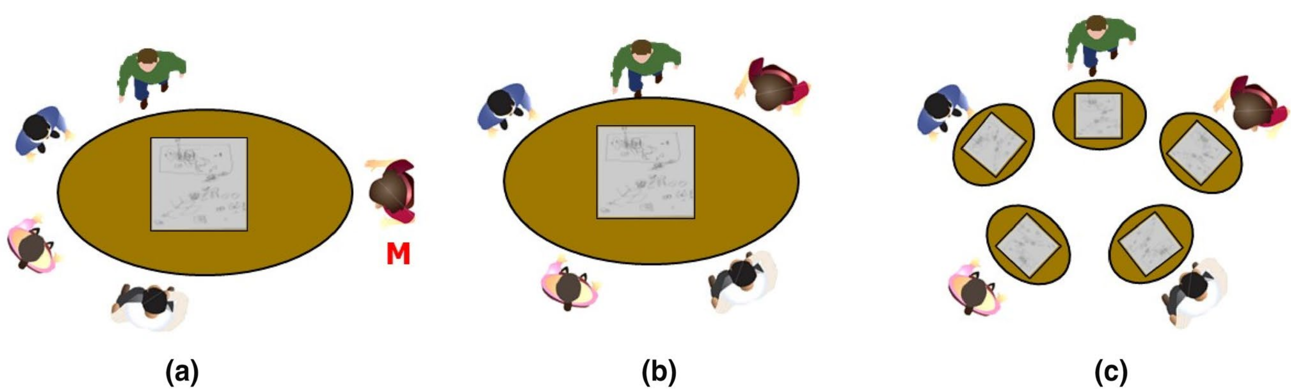

Fig. 1 Participants were randomly assigned to one of the three team conditions: **a** managed team, an **b** unmanaged team, or a **c** nominal team

compiled. For the three intervention types, the six answers with the highest frequency between the chosen managers were aggregated to form the *manager bank*, shown in Fig. 2. During the ensuing study, the process managers were only allowed to select from these 18 specific examples, that comprised the three categories, to intervene with. This compilation was done to control for variability and to maintain some consistency in the types of interventions. The keywords and design components in the bank were printed on cards that were physically handed to the design teams, while the design strategies were verbally spoken by the managers, all done when deemed appropriate. All in all, the study was purposefully designed to minimize the impact of differences or limitations in managerial skill, by recruiting graduate students with both design knowledge and leadership experience, and creating the *manager bank*, from which they were restricted to apply.

Prior to the experiment, the graduate students were required to participate in a 30-min training session. During this session, which was led by one of the research investigators, the managers were trained on the experimental procedures. Other than reading the instructions, answering logistical questions, and intervening with a design strategy, the managers were not allowed to speak during the experiment. The managers were also told to keep notes on the exact times and types of interventions they used during the study with their teams. It was also emphasized to them that they were not to help their team in directly solving the design problem, but were there only to manage their team's design process.

Within 2 days following the experiment, a post-study interview was also conducted with each manager. During these interviews, the research investigator went through each intervention and asked the managers: "*What made you interact* [with item x]", "*Why did you interact with what you did*", and "*What was the effect of your interaction?*" The primary goal of these interviews was to determine what prompted the managers to interact with their teams, to gain a deeper understanding into the rationale underlying these interventions. During these interviews, the managers were allowed to refer back to the notes they had taken during the study, to facilitate in their recollection of events, if necessary.

2.3 Experimental protocol and materials

The students' 1-h and 50-min class period was broken up into two 55-min intervals. Half of the class was assigned to group A while the other half of the class was assigned to group B. While group A participated in the experiment for the first 55-min period, the other group received a lecture on engineering ethics, an agreed-upon request between the researchers and course instructor for running the study during the class period. For the second half of the class, the two groups switched. Within a group, students were evenly and randomly distributed among the different experimental conditions. The same experimental materials were provided to all participants, regardless of the team condition they were in. These items include a pen for each individual on a team and 3 sheets of 11″ × 17″ white, multipurpose paper. In the managed and unmanaged team conditions, the three sheets of paper were shared among the entire team to promote collaboration, while in the nominal condition, each individual received three sheets. Prior to participating in the experiment, individuals were asked to read and sign a consent form.

During the experiment, participants were given 30 min to solve the following engineering design problem (Fu et al. 2010; Linsey et al. 2010; Gyory et al. 2018a):

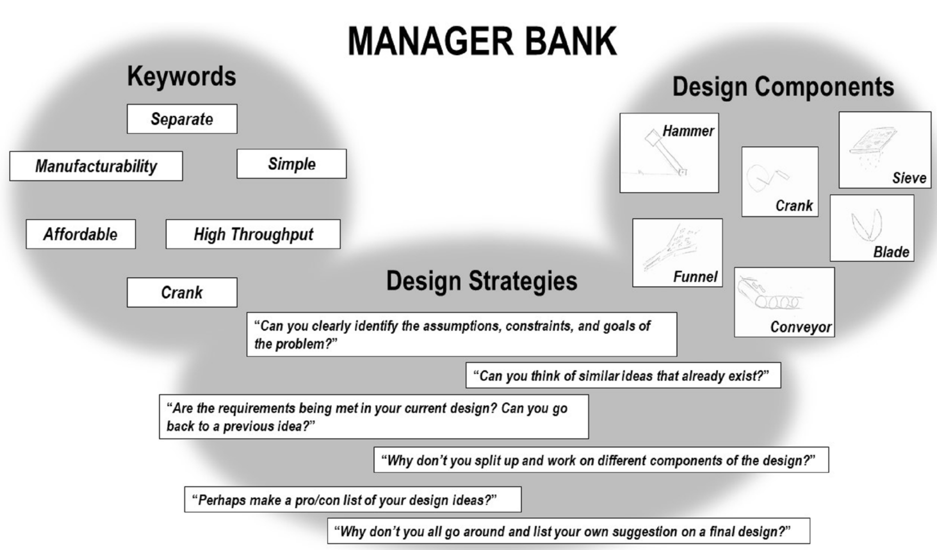

Fig. 2 The collection of intervention stimuli which the process managers were able to use during the experiment

Problem statement:
Design a low-cost and easy-to-manufacture device that removes the outer shell from a peanut

Constraint 1:
The device is meant to be utilized in developing countries where electricity may not necessarily be available as a power source

Constraint 2:
In addition to the previous constraint, the proposed design must be able to separate a large quantity of peanuts from their shells, while causing minimal damage to the inner peanut

To simulate a real-world, dynamically changing engineering problem, the two constraints were sequentially introduced 10 min and 20 min, respectively, into the study. These added constraints were meant to exacerbate the problem difficulty throughout problem-solving. An overview of the experimental timeline is shown in Fig. 3.

Participants were allocated the entire 30 min to problem-solve. To distinguish this task from a pure, creative brainstorming session, participants were told from the onset that they could initially (and were encouraged) to discuss and sketch about as many possible ideas for the problem, but by the end of the experiment, had to come up with a single design solution. This instruction was to encourage problem-solvers to eventually bring closure to (i.e., select a concept), and potentially, iterate upon their final design. Each time a constraint was introduced during problem-solving, they were instructed to continue their sketches on a new sheet of paper that was provided to them. By the end of the experiment, each team had three sheets of sketches, with the last sheet containing their final solution. Using audio recorders, both managed and unmanaged teams' discourse was also collected throughout the experiment. At the conclusion of the experiment, one team member from these two conditions was also asked to provide a brief, verbal description of the group's final design. The individuals and unmanaged teams were under the supervision of passive experimenters, who only read the experiment instructions, monitored time, and provided the experimental materials (sheets of sketching paper and constraints to the problem). In the managed condition, these same procedural responsibilities were assigned to the process managers.

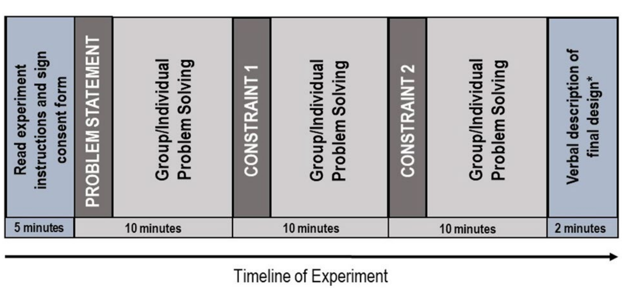

Fig. 3 The experimental timeline showing the introduction of the problem statement, constraints, and blocks of problem-solving. *Audio was not collected from the individuals (i.e., nominal teams), so they did not provide a verbal description

3 Data analysis

3.1 Ideation metrics

To compare the performance between the collaborative and nominal teams, their final designs from the end of the experiment are evaluated. According to Shah et al., accurate measures of ideation effectiveness, as well as how problem-solvers explore within the design space, can be seen in the *novelty, quantity, quality*, and *variety* of their design output (Shah et al. 2003). However, because the participants in this experiment are told to only come up with one final design solution, and both quantity and variety are a function of the number of ideas generated per individual, only the novelty and quality are used in this analysis. In practice, products need to work, but they do not need to be novel; thus, an effective solution is required while a novel solution is only desired. Thus, novelty, or *uniqueness*, of a solution is secondary to quality, given that low-frequency solutions are not necessarily good solutions, they are simply rare. Therefore, the teams' final designs are evaluated based on these two ideation metrics, with quality taking precedence.

3.2 Design quality

The *quality* of a design refers to its technical feasibility and how well a particular solution satisfies the engineering specifications of the problem. Two mechanical engineering graduate students at Carnegie Mellon University, with extensive experience in design theory and methodology, rated the quality of the final designs based on how well a solution satisfies the constraints of the design prompt. Ratings are coded into the three distinct categories shown in Table 1.

This three-point rating scale was chosen to minimize the subjectivity inherent in larger rating scales, at the expense of losing resolution in the scores, while enabling a judgement of excellent, acceptable, and poor. The raters were provided with brief instructions, the problem statement and constraints used in the study, and the corresponding category descriptions from Table 1, but did not receive any further training on how to score the designs. Because each design is scored by both raters, each design has two associated quality values.

3.3 Design novelty

The *novelty* of a design solution defines how unconventional or unusual an idea is compared to other designs,

Table 1 Quality rating categories

Rating category	Category description
0	The design violates a constraint/function of the design problem
1	The design poorly satisfies the constraints/functions of the design problem
2	The design effectively satisfies all constraints/functions of the design problem

within the set of designs generated within the experiment. This definition represents the breadth of search through the design space. The authors prefer the term *uniqueness* as these designs may not have value or be truly rare beyond this study; however, for consistency with the design literature and by assimilation of the Shah et al. metric, the term novelty is used in this paper. A posteriori evaluation of novelty is computed, in which comparisons are made relative to the ideas generated between participants during the experiment. Therefore, the design space is populated with only those designs from the experiment. The novelty is calculated by looking at the different sub-functions of a design and identifying what mechanism is used to satisfy that sub-function. To meet all the engineering requirements of the problem statement from the study, an adequate solution can be broken down into five distinct sub-functions that must be satisfied by the design (each with an associated weight f). These include an energy conversion (human/natural to mechanical) mechanism (f_1), transportation of the peanuts through or along the device (f_2), crushing/de-shelling of peanut shells (f_3), sorting of the intact peanuts from their crushed shells (f_4), and the collection of the harvested peanuts (f_5). Shah et al. formulate the posteriori computation of the novelty, N, of a team's design as

$$N = \sum_{j=1}^{n} f_j \sum_{i=1}^{m} \frac{T_{ji} - C_{ji}}{T_{ji}} \times 10 \times p_i, \tag{1}$$

where T_{ji} is the total number of ideas generated for sub-function j, C_{ji} is the count of the current solution for function j, f_j is the weight assigned to function j, signifying its importance, n is the total number of sub-functions (in this case, $n = 5$), m is the particular stage of the design process, and p_i is the weight associated with that stage. Because the focus is only on one phase of the design process, the ideation phase, the above equation reduces to

$$N = \sum_{j=1}^{n} f_j \frac{T_{j1} - C_{j1}}{T_{j1}} \times 10. \tag{2}$$

The multiplication of the constant 10 is to normalize the novelty scores on a scale from 0 to 10. The weights, f_j, for each of the five sub-functions are chosen based on the experimenter's estimated importance of the sub-functions' contribution to the overall design problem. Accordingly, the chosen weights for the sub-functions to compute the overall novelty scores are $f_j = \{0.25, 0.10, 0.35, 0.20, 0.10\}$, where $1 \leq j \leq 5$.

3.4 Generation of nominal teams

To compare the performance of both the managed and unmanaged teams with the individual problem-solvers, nominal teams are generated. Nominal teams are teams composed of individual problem-solvers who did not interact during the study, but are artificially placed together to form a team. Then the cumulative best solution amongst the individuals' solutions is considered the product of the entire team. In this experiment, five individuals are placed together so that they can be compared with the other team conditions. The nominal teams are computationally formed with a random number generator, under the following constraints: (1) all 23 individual problem-solvers need to be placed on a team, (2) all but six individual problem-solvers needed to be assigned to two different teams (assuming eight total teams with five students on each), and (3) every team had to consist of five unique individual problem-solvers. This algorithm is repeated until eight valid nominal teams are generated. This random assignment removes any bias that could be formed, because all members were equally likely of being selected for a team. In this experiment, the solution with the highest quality is chosen as the team solution. The intuition behind this is that, in practice, when individuals on a team select between possible designs (or their supervisor selects amongst candidate solutions), the design with the best quality would likely be the one chosen. If two designs are comparable with respect to their quality, then the design with the higher novelty is selected as the preferred idea. With this method, it is possible that a significantly superior design (in terms of quality and novelty) could appear on multiple teams. However, at most, an individual could only be placed on two different teams and, therefore, that design could only be considered at most twice.

3.5 Team cohesion

In addition to measuring the solution output from the design teams, the teams' dynamics are investigated. The audio recordings from the experiment are used for this purpose to measure the similarity of a teams' discourse, i.e., the team cohesion, and how it evolves throughout problem-solving.

Latent semantic analysis (LSA) has been shown to quantify this level of semantic convergence in language-based communication between members in design teams (Dong 2005). The degree of a team's cohesion has been shown to be directly proportional to their cognitive representation of the design problem, and is accepted as an accurate measure of a team's design performance (Dong et al. 2004). Because the individual problem-solvers that comprised the nominal teams were not audio recorded during the experiment, only the collaborative teams can be compared with one another with this measure. Therefore, this analysis will facilitate in addressing only the second research goal of this work: the impact of process management interventions on engineering teams.

As background, LSA uses singular value decomposition (SVD) to determine the underlying patterns within text (here speech) by projecting the co-occurrence of words across documents (here speakers) to a lower rank (dimensional) approximation of the semantic space (Landauer and Foltz 1998). The SVD of a matrix, X, is shown in the following equation:

$$X = USV^T. \tag{3}$$

For this experiment, matrix X is an $[n \times m]$ occurrence matrix with n number of words and m speakers, U is an $[m \times r]$ concept vector matrix with rank r, S is an $[r \times r]$ singular values matrix, and V is an $[n \times r]$ speaker matrix, containing speaker vectors. By mapping the co-occurrence of words into this new r-dimensional semantic space, the cosine similarity between speaker vectors can be computed to determine how closely related speakers' semantic coherence is. The overall semantic coherence of a design team is then computed by taking the average of all pairwise cosine similarities between members of a team.

The pipeline for post-processing the audio files and running LSA to compute the semantic coherence is depicted in Fig. 4. The text corpus for LSA is generated from the audio files recorded during the study. First, each audio file is transcribed, via an outsourced vendor, into a single transcript for each design team (step 1). Each transcript is then checked and verified for proper speaker identification. The speakers are then segmented out of the full experiment transcripts to obtain a text document representing each speaker on a team (step 2). For the managed teams, the manager document is excluded from the analysis because they are not included when computing the semantic similarity of a design team. The occurrence matrix, X, is then generated for each team (step 3) and weighted using the global, log-entropy (Eq. 4) across speaker documents of a team (Harman 1986):

$$W = 1 + \sum_j \frac{p_{ij}\log_2\left(p_{ij}\right)}{\log_2(m)}, \tag{4}$$

where P_{ij} is the ratio of the frequency of each term in a document to the frequency of each term over all documents.

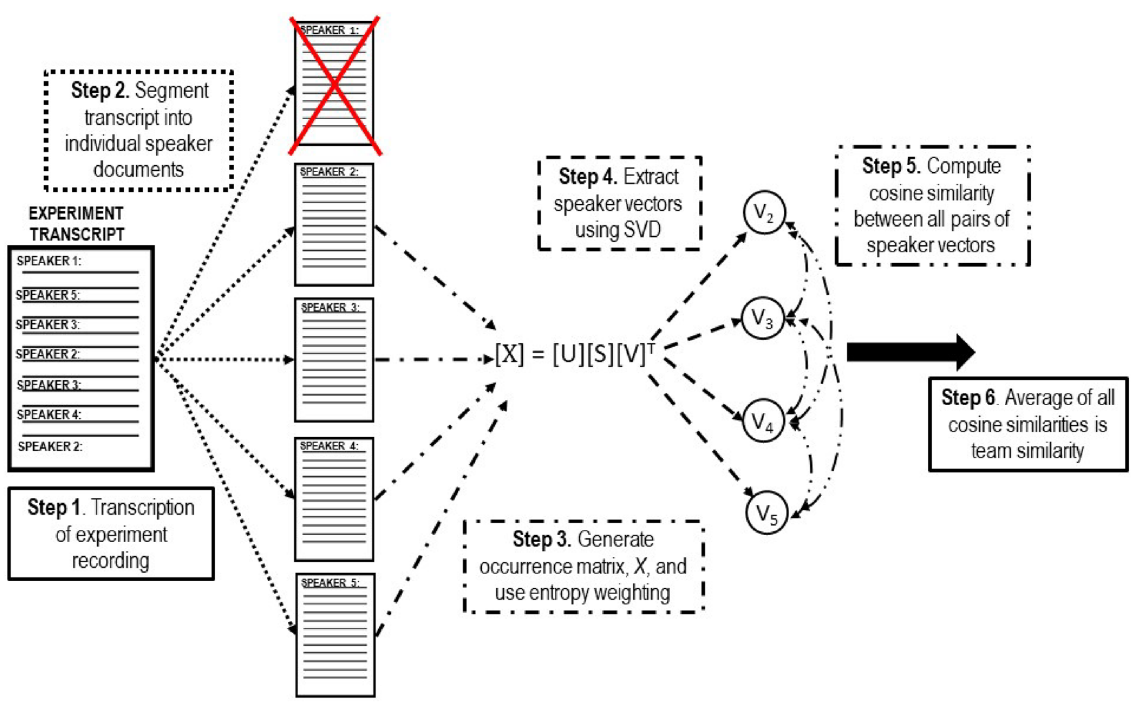

Fig. 4 Representation of the pipeline for running latent semantic analysis (lsa) on the audio transcriptions

This global entropy weighting is used to dampen the effects of large differences in the frequency of words (i.e., gives less weight to terms that occur frequently or are commonly used, and more weight to terms that are less frequently used). After weighting the occurrence matrix, SVD is performed (step 4) to reduce the dimensionality of the matrix, and speaker vectors are then extracted. The cosine similarity is then computed between all pairs of speakers (step 5) and the average of those comparisons is taken as the team's semantic similarity (step 6).

3.6 Manager interventions

The transcripts from the experiment are utilized, in conjunction with the post-study interviews, to designate the timing and type of managerial interventions. This exploratory analysis will provide insight into some of the managerial techniques and strategies utilized by the managers at different points in the design generating process. To do this, comparisons are made across three, equal 10-min intervals of the experiment, which are delineated based on when the constraints were added to the problem (i.e., before the first constraint was given, between the first and second constraints, and after the second constraint).

4 Results

At the conclusion of the study, participants are instructed to have their single, final design circled. For both the managed and unmanaged teams, this solution is collaboratively chosen by all members on a team and, therefore, is representative of an entire team's effort. These elected designs are extracted from the last sheet of sketches and utilized in the assessment of the previously discussed ideation metrics. A sample set of final design solutions from each team condition is shown in Fig. 5.

4.1 Design quality

As discussed in the analysis section, each design is rated for quality by two mechanical engineering graduate students as either 0, 1, or 2, depending on how well the solution satisfies the problem statement and design constraints. Figure 6 shows the frequency of designs binned into each of the categories, with the x-axis representing the three quality categories and the y-axis being the frequency of designs in each respective bin. Due to some subjectivity in this assessment, each design is scored by both graduate student raters,

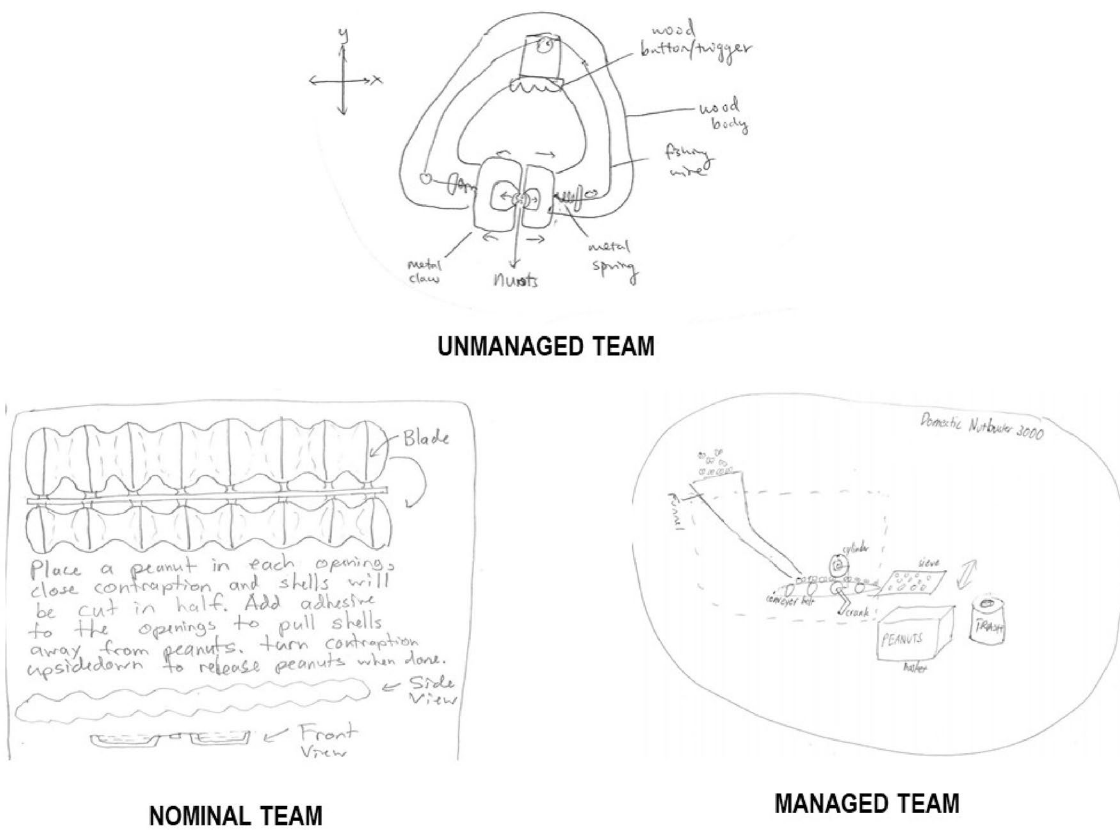

Fig. 5 Example final design solutions from an unmanaged (top), a nominal (bottom-left) and a managed (bottom-right) engineering design team

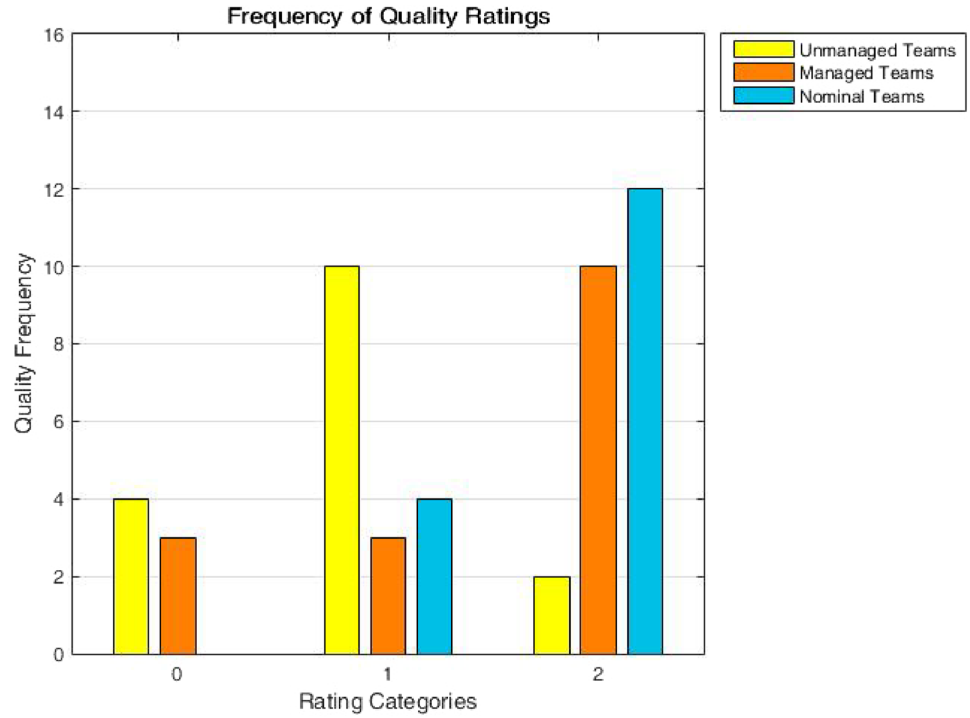

Fig. 6 Frequency of quality ratings for unmanaged teams, managed teams, and nominal teams

to maintain consistency and objectivity in the scoring. To gain a sense of the degree to which the raters are consistent with one another, the intraclass correlation coefficient (*ICC*) is computed across all designs ($ICC = 0.58$), which is an acceptable correlation (Cicchetti 1994).

Because the data are ordinal and not normally distributed, a Mann–Whitney *U* test, the non-parametric version of the *t* test, is run. The test reveals that both the managed teams ($p < 0.014$, effect $r = 0.39$) and nominal teams ($p < 0.001$, effect $r = 0.64$) generate designs of significantly higher quality than the unmanaged teams. The nominal teams' designs tend to be of slightly higher quality than those of the managed teams ($p < 0.15$, effect $r = 0.18$). Thus, the first research goal, of whether the performance of individuals surpasses teams in the domain of conceptual engineering design, can now be addressed. Indeed, the higher quality designs generated by the nominal teams, compared to unmanaged teams, are indicative of better overall performance.

4.2 Design novelty

The final designs are evaluated using a posteriori measure of novelty (i.e., *uniqueness*), which describes how uniquely each of the five sub-functions are satisfied in a given solution, compared to the other solutions within the experimental design space. Table 2 provides a summary for each of

Table 2 The count of different mechanisms used in design teams' solutions

Novelty scores, a posterior mechanism counting

Energy Conversion ($f_1 = 0.25$)	C_{11}	Transportation ($f_2 = 0.10$)	C_{21}	Crushing ($f_3 = 0.35$)	C_{31}	Sorting ($f_4 = 0.20$)	C_{41}	Collection ($f_5 = 0.10$)	C_{51}
Bike Pedal	3	Wind	1	Rollers	5	Sieve	8	Bucket/Basket/box	11
Crank	8	Conveyor	4	Lead Screw	1	Fan	2		
Lever	1	Inclined Slope	4	Hammer	1	Mesh	2		
Pivot	1	Gravity	3	Blade	1	Mold	1		
Spring	2	Funnel/Cylinder	4	Cylinder	2	Wedge	1		
Hinge	3	Rollers	2	Scissors	1	Spikes	1		
Human/Manual	4			Friction	4				
				Crusher	7				
				Claw	1				
				Human force	1				
$T_{11} =$	22	$T_{21} =$	18	$T_{31} =$	24	$T_{41} =$	15	$T_{51} =$	11

the five sub-functions and the count (C_j) of each mechanism used to satisfy them. Summing these counts for each sub-function identifies how many teams in total, T_i, satisfy a particular sub-function, where i ranges from 0 to 24, for 24 total design teams (eight in each of the three conditions).

In reference to the total counts, T_j, the only sub-function that is satisfied by all 24 teams is the crushing function, f_3. The energy conversion sub-mechanism is the next highest, followed by the transportation function. This result is consistent with the chosen weights, f_j, that were discussed previously. For example, the sub-functions given the higher weights end up being fulfilled by more design teams, signifying their lack of ambiguity from the problem statement and importance to the overall design task. Substituting the counts (C_j) and totals (T_j) from Table 2 into Eq. 2, the novelty scores can be calculated for each team. Figure 7 shows that the managed teams have a significantly higher measure of novelty than both the nominal ($p<0.01$, $d=1.35$) and unmanaged teams ($p<0.007$, $d=1.41$). There is no significant difference between novelty of unmanaged and nominal teams' designs.

To determine whether the experimenter's chosen values of the weights impact the results of the novelty, a sensitivity analysis is performed on the novelty formulation. The functions are first weighted equally ($f_j=0.2$), for each sub-function (equivalent to no weighting at all). Re-computing the novelty, the results are identical to that originally found, with the managed teams exhibiting higher novelty than both unmanaged and nominal teams; the latter two having no significant difference. Furthermore, to determine the sensitivity of the novelty score to the value of the individual weights, each weight is successively perturbed $\pm 10\%$ from its original value and the novelty is re-determined. When one weight is perturbed, the four remaining weights are readjusted so that the total weight sum remains at 1 $\left(\sum_{j=1}^{5} f_j = 1\right)$. After recalculating the novelty with each new combination of weights, in every case, the managed team's novelty score remains highest, and the unmanaged and nominal teams lower and similar. This analysis confirms that the scores are not sensitive to the originally chosen weights (which were, $f_j=[0.25, 0.10, 0.35, 0.20, 0.10]$, for $1 \leq j \leq 5$), and this weighted set will be the one used for purposes of this work.

4.3 Team cohesion

Now that nominal teams have been shown to produce higher quality solutions than unmanaged teams, the second research goal can be addressed, namely whether a manager is able to mitigate the costs associated with collaborative engineering design teams. From Figs. 6 and 7, the teams under the guidance of a manager generate solutions that are both significantly more novel and of slightly higher quality than the unmanaged teams. Post-processing the audio transcriptions according to the pipeline outlined in Fig. 4 and running LSA on these transcriptions (Fig. 8), the managed teams' discourse exhibit higher semantic similarity over all three experimental intervals ($p=0.016$, $p=0.026$, $p=0.015$, respectively). This result further supports the claim that the process managers are able to mitigate some

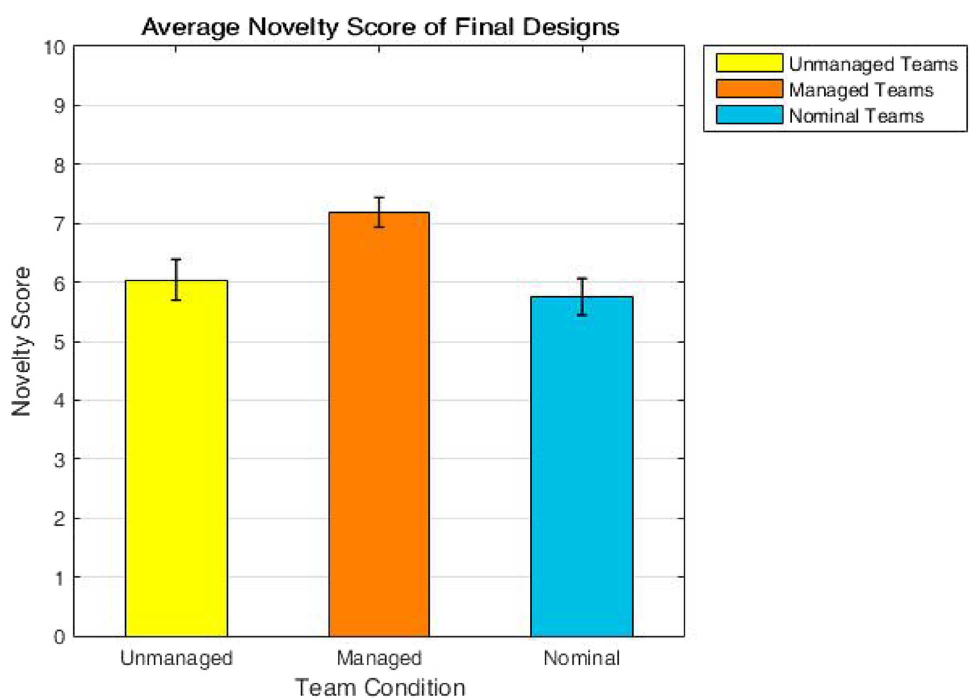

Fig. 7 Average novelty scores for unmanaged, managed, and nominal teams (error bars show ± 1 SE)

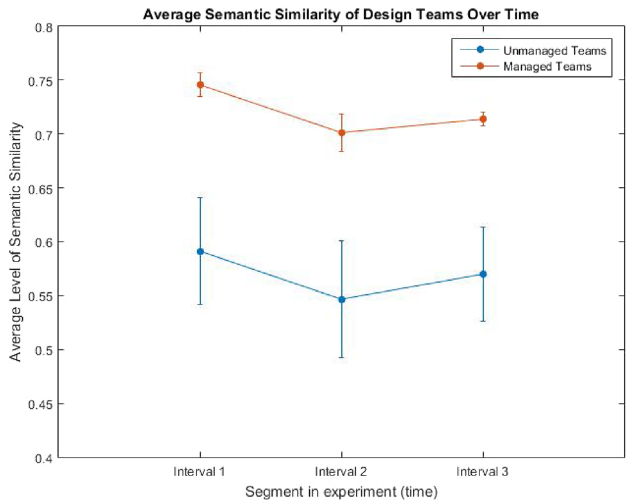

Fig. 8 Latent sematic analysis on audio recordings of design teams (error bars show ± 1 SE)

of the performance costs of engineering design teams. It is also interesting to note that both team conditions exhibit a similar and consistent trend, showing a decrease in cohesion between the first and second intervals, followed by a small increase in the third interval.

4.4 Process management interventions

Since process managers are shown to be beneficial, a preliminary analysis into some of these constructive managerial strategies can be done by examining the frequency and types of interventions throughout the experiment. A general summary of all the manager interventions is shown in Fig. 9. As a recap, the allowable types of manager interventions are the *keywords, design components*, and *design strategies* that were depicted in the *manager bank* (Fig. 2).

The managers were able to interact with those prescribed items but could not otherwise speak with the design teams or help in directly solving the problem. In total, the managers intervene 52 times with 11 interventions in the first interval, 25 interventions in the second, and 16 during the final interval. Of the 52 interventions, 42% are design components, 31% are keywords, and 27% are design strategies. To understand the evolution of managerial strategy over the different problem-solving phases, Fig. 10 depicts the temporal evolution of interventions. The percentages shown are relative to the number of interventions per interval. For example, 45% of the design strategy interventions in the first interval equate to five distinct design strategy interventions. Overall, the design strategies and keywords comprise the majority of interventions in the first segment of the experiment, with a more equal distribution among all three types in the middle. By the end of the experiment, the largest proportion of

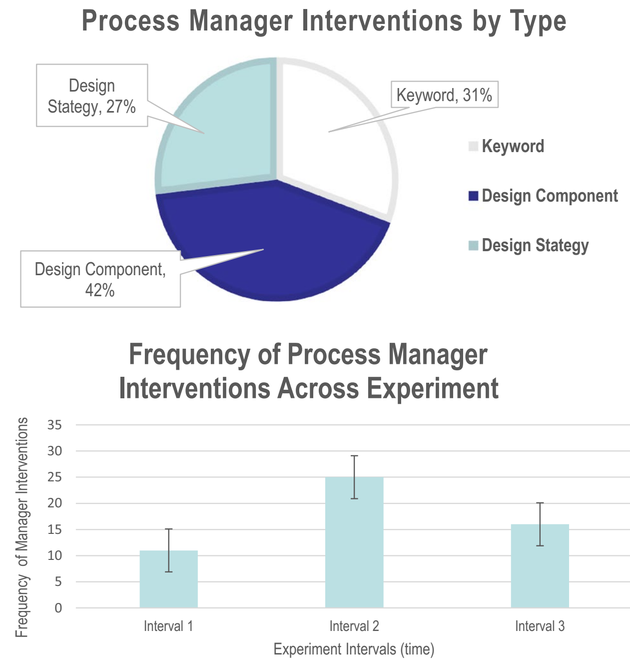

Fig. 9 Overview of manager intervention usage over the entire experiment by type (top) and frequency (bottom) (error bars shows ± 1 SE)

managerial interventions is design components as the final design ideas are instantiated.

The post-study interviews with the graduate student managers are also evaluated to uncover the underlying motivations. This is useful for determining the rationale, and consequently, the feedback the managers used in deciding the most opportune times of intervening. After analyzing the interviews and sorting the interventions into common themes, four salient motivations emerged: assist the team in generating new ideas, help the team promote their current thought, remind the team of the engineering design requirements, and improve the team dynamics. To get a better sense of

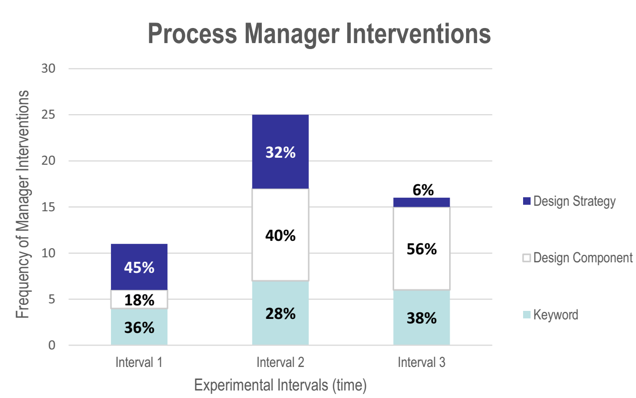

Fig. 10 The evolution of managerial interventions during each experimental interval

how these motivations are binned, consider the ones shown in Table 3.

For example, asking a manager why they intervened with the design strategy, "*Can you think of similar ideas that already exist*", they responded with the first statement from Table 3: "*There was no structure to their thought process, and there was no direction*". This intervention is characterized as "help generate new ideas", because the engineering design team was not focused and having difficulty deciding how to approach the problem and brainstorm initial ideas. Each of the 52 manager interventions is analyzed and categorized in this way, by associating with it an underlying motivation.

Similar to the intervention types, these motivations are examined across the three experimental intervals. The progression of managerial motivations is shown in Fig. 11. The percentages are, again, relative to the number of interventions per interval. For example, 18% of the "reminder of engineering design requirements", in the first interval equates to two distinct interventions. One central trend captured in Fig. 11 is the steady increase of "reminder of engineering design requirements". This evolution suggests that assisting design teams in focusing on the constraints of the problem and attributes of their designs is an increasing objective of the process managers throughout the entire problem-solving process. This is true, particularly near the end of the experiment, when 75% of the interventions are categorized by this motive.

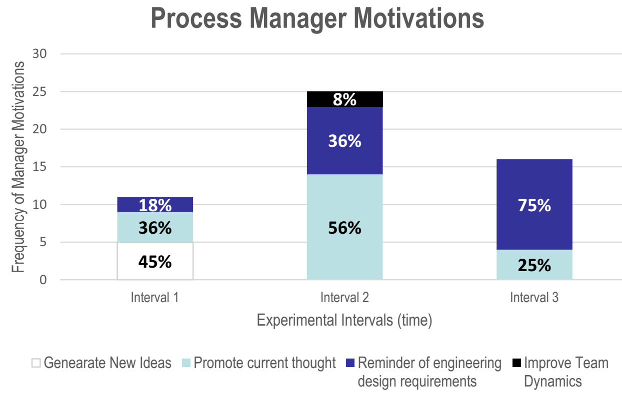

Fig. 11 The evolution of managerial motivations during each experimental interval

4.5 A possible mechanism: verbalization

Even though process management, in this experiment, is shown to be beneficial to design teams, individual problem-solvers still perform marginally better in terms of their collective solution quality. One of the main differences between individual and collaborative team problem-solving is the fact that teams need to verbalize to communicate ideas with one another. Sio et al. previously investigated the effect of this communicative process on RAT problems, and found that thinking-aloud nominal groups were impaired in comparison to nominal groups who solved the problem quietly (Sio et al. 2018). Perhaps this could be one of the main cognitive hindrances and costs of group problem-solving, and one that the process management in this experiment is not able to mitigate.

Consequently, a supplemental condition is run to examine the effects of verbalization during problem-solving, and to see if individuals who verbalize perform worse than individuals who do not verbalize during problem-solving. The experimental architecture and logistics are identical to the previous nominal team group, except that participants are also told to think aloud during problem-solving so that their thoughts on conceptualization could be followed. The time was carefully monitored, and if an individual went 10 s or longer without expressing their thoughts, the experimenter reminded them to continue verbalizing. In total, 22 additional freshman engineers participated in this condition of the experiment, and nominal teams were generated following the same algorithm discussed earlier. The designs were evaluated in the same way, and the results are shown in Fig. 12.

While the differences are in the right direction (silent outperforming speaking), there is no significant difference in the quality of design solutions between individuals who solve problems silently and those who concurrently

Table 3 Example motivations from post-study interviews with managers

Managerial motivations
Help generate new ideas
"There was no structure to their thought process, and there was no direction"
Promote current thought
"They were thinking through a bunch of human interfaces and they hadn't really considered a crank, and I thought a crank would be a useful extension to the one's they had considered"
Remind of engineering design requirements
"They had only focused on crushing the shell at that point and not thought about how to actually get the center of the peanut out of the shell"
Improve team dynamics
"There was really one person leading it and I wanted everyone to have something to do and have them take different tasks"

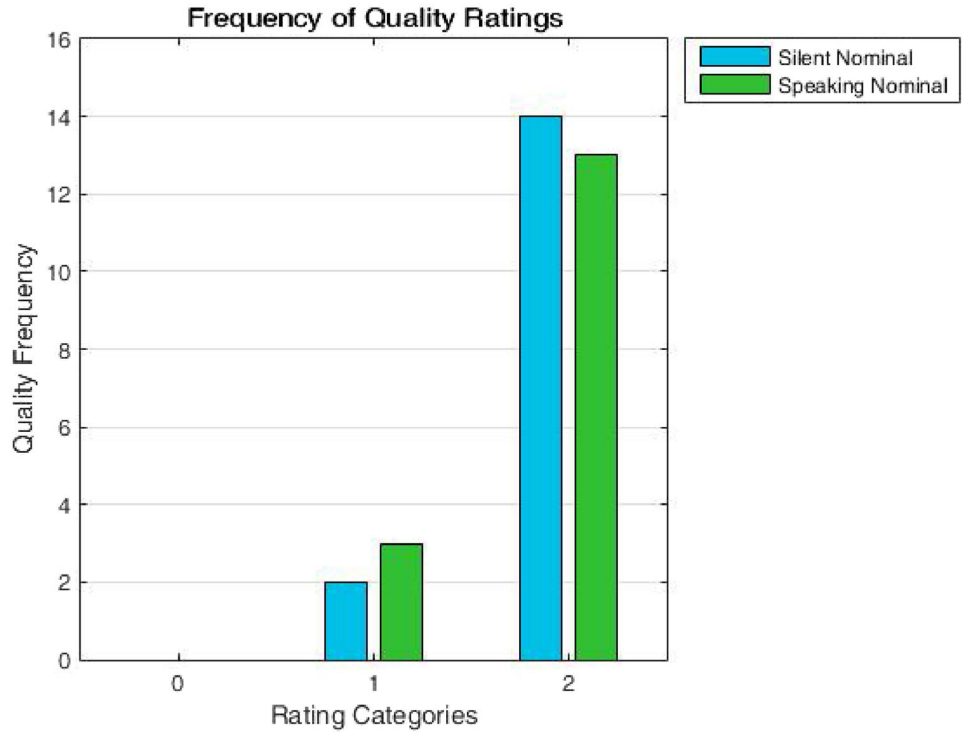

Fig. 12 Frequency of quality ratings between silent nominal teams and speaking nominal teams

verbalize. The inconsistency of this result with the results from the RAT problem task is likely due to a fundamental difference in the tasks: in particular, the difference in the cognitive processing of spatial and verbal tasks. As shown by Brooks (Brooks 1968), tasks that are verbal in nature, such as the RAT problems, will be hindered by concurrently performing a task that is also verbal, such as thinking out loud, while spatial tasks, in his case visualizing action on a block letter, will not be so affected. Conceptual design is more of a spatial-oriented problem (Hsi et al. 1997); thus, verbalization should not, and turns out does not, act as a cognitive barrier while concurrently solving the design problem, due to this difference in the form of processing. Thus, verbalization does not seem to be a direct cognitive barrier to this type of team problem-solving, and additional work must be done to try to identify what features of collaborative teams put them at a disadvantage to individuals in conceptual engineering design.

5 Discussion

5.1 Effects and general strategies of process management

As introduced at the beginning of the paper, this research presents two primary goals. The first is to determine whether the performance of individuals (i.e., *nominal teams*) is superior to that of collaborative team problem-solving in conceptual engineering design, a domain which shares the free-flowing, creative aspects of brainstorming, but possess the goal-oriented and structured characteristics of configuration design. The results from this study support this claim, showing that unmanaged engineering design teams are not as proficient as individual problem-solvers. Nominal teams generate design solutions of significantly higher quality. Exploiting this result, the second aim of this work is to examine whether the underperformance of these design teams can be mitigated with resources allocated to the management of the design process via a human manager. The effects of a manager to the problem-solving process show that these teams do benefit, even when resources are taken away from directly solving the problem. The managed teams, with one less member and, therefore, fewer direct problem-solving resources, still perform better, with significantly higher quality design solutions than unmanaged teams. These teams also produce final designs that are of greater novelty (*uniqueness* across the set generated)—and are more cohesive throughout the experiment, as measured through the semantic similarity of their verbal discourse. Thus, the findings from this study show that real-time management of the design process closes the performance gap between individual problem-solvers and teams. However, the nominal teams still produce designs of marginally higher quality than the teams that are managed, suggesting that there are still some deficiencies in design teams that managers are not able to mitigate.

Given that the process management of design teams is shown to be beneficial, analyses can now focus on uncovering some of the constructive intervention strategies. Generally, the managed teams satisfy a greater number of the five identified sub-functions of the design problem, and in more unconventional ways than teams in either of the other conditions, resulting in higher novelty of their final designs. Of the 12 mechanisms, in Table 2, that are used by only a single design team (i.e., the most unique mechanisms), half of those are from managed teams. The set of these mechanisms includes lever, pivot, wind, lead screw, hammer, and scissors. Also, as depicted in Fig. 11, reminding teams of the engineering design requirements is the only motivation that considerably increases throughout the entire experiment. This suggests that the managers play a major role in getting their teams to think about all requirements of the design.

Another significant trend in the manager interactions is the usage of the design component stimuli, which increases from 18% of the manager interventions in the first interval to 56% by the final segment. Because the design components are all specific mechanical elements, this trend is also consistent with the managers reminding their teams to consider the functional aspects of the design. For example, providing a team with the conveyor stimuli could prompt a design team to focus on the transportation of the peanuts through the device. Similarly, providing a team with the sieve component helps teams to concentrate on sorting the peanuts from their shells. One could argue that the managed teams become fixated and directly use the components that are provided to them during the interventions. Because the managers are trained not to speak when intervening with the design components, some of the participants may have perceived these particular interventions as additional requirements to the design problem. Even so, this does not undermine the fact that, overall, the managed teams' designs are more novel. Also, as shown in Table 2, out of the most novel mechanisms (those with a count of 1), only the hammer design component is taken directly from the manager bank. As such, fixation on the specifics of manager suggestions is an unlikely implication from the interventions.

Collectively examining the types and frequency of interventions over all three experimental intervals (Fig. 10), coupled with the compilation of motivations (Fig. 11), yields valuable insights into the managerial strategy and how it evolves throughout problem-solving. The design strategies comprise the largest proportion of interventions in the first interval of the experiment (46%). This result suggests that toward the beginning of ideation, the managers want their teams to follow a more encompassing and exploratory search of the design space. Specifically, "*Can you think of similar ideas that already exist*" and "*Can you clearly identify the assumptions, constraints, and goals of the problem*" are the two significant design strategies suggested by managers in the early stages of the experiment. Similarly, in the first 10 min of the study, 46% of the interventions are motivated toward helping their design teams generate new ideas. This result agrees with the types of interventions, because in the early stages of brainstorming and ideation, effective exploration of the design space is important. As problem-solving proceeded, the most frequent interventions focused on design components, with 56% of the interventions in the final experimental interval. The increasing implementation of design components, particularly near the end of the experiment, indicates that the managers try to get their teams to hone in on a specific region, or subset of solutions, within the design space, to instantiate a final effective solution. Overall, it seems that the predominant tendency in managerial behavior is to push their teams to follow an exploratory-to-convergent search of the design space, which has been shown to be an effective strategy for concept generation and creativity in design problems (Thompson and Lordan 1999; Liu et al. 2003), and thinking in design teams (Stempfle and Badke-Schaub 2002). This exploratory-to-convergent funneling of design team efforts is also mirrored by the manager motivations, with 75% of the interventions in the last interval being prompted by reminding teams of the engineering design requirements. This rationale is critical in final design convergence and selection when improvements and iterations must be done to achieve all the engineering design specifications.

5.2 Limitations and future work

It should be acknowledged that the results from this work are prognostic as opposed to purely diagnostic. The underlying reason of why nominal team performance is superior is still an open question and requires future work to make any definitive conclusions. Perhaps some of the recognized deficient team characteristics from other literature, such as social loafing, may be at play here (Comer 1995). In observing the interaction of teams during the study, for example, it appeared that some members did not participate as much as others; thereby indicating that social loafing could be the cause. Also of note, both the teams and individuals evolve what they perceive to be their best design. However, in the team condition, biases in decision-making and other team characteristics may possibly have influenced and inhibited the selection of their actual best design (Jones and Roelofsma 2000; McComb et al. 2015b). By the current definition of a nominal team, the best design amongst the collection of individuals is automatically chosen for them. This discrepancy in selection could have affected the difference in collaborative and nominal team performance, though this, and other theories that might account for the inferior performance of the design teams, are left for future investigation.

Nonetheless, supplying process management did mitigate the negative effects of working in teams.

Moreover, the team structure in the experiment is both static and free; the structure does not change throughout problem-solving and all members are free to communicate with all other members without any limitations. This structure could also have negatively affected and led to the inferior performance of design teams. Additional work on modeling different team structures which have shown to be more effective (Siggelkow and Rivkin 2005; Kavadias and Sommer 2009), such as hybrid teams, where individuals initially work on the problem separately before coming together to collaborate (Girotra et al. 2010), could be an interesting direction.

To gain a deeper understanding into managerial behavior, future work can focus on a more refined and in-depth analysis of the manager interventions to extract specific modalities and timing that are most beneficial to design teams. The evolution of each teams' designs may also be tracked through the experiment to see how designs are affected by these interventions and whether managers help teams overcome some of the stumbling blocks associated with problem-solving. The process managers were also recruited with similar skillsets and constrained in the types of interventions that could be used; this was purposefully done to equalize management capabilities and reduce variability. Although fixation was not seen as directly impacting the teams (as the managed teams had more novel ideas), it would be interesting to see how enlarging the manager bank to create a more expansive example set, as well as changing the managers' expertise, impact the design process (Agogué et al. 2014; Ezzat 2017). Different evaluation metrics could also be studied, such as creativity, to determine how feedback influences such (Ezzat et al. 2017). Because this study utilizes freshman engineering students from an academic institution and limits the problem-solving process to a short time frame, there are still unanswered questions about the generalization of the results outside the lab setting. Thus, future work can also consider if the results and observations from this current work extend to a larger scale and apply to engineering design teams in practice.

6 Conclusion

This paper presents an empirical study to investigate individual versus group performance in the domain of conceptual engineering design. Accordingly, a behavioral experiment is run, in which freshman engineering students solve a conceptual design problem individually or in a collaborative team setting. Corroborating previous findings, those who work on the problem individually, when the cumulative best solution is selected, end up generating solutions of much higher quality than those who work in unmanaged teams. An attempt to mitigate some of the deficiencies associated with design teams is then made by introducing a third condition, where partial resources are taken away from problem-solving and reallocated to the process management of the team. Teams that are guided by this process management perform nearly as well as individuals, suggesting that, perhaps under the proper direction, teams can become as efficient as individual problem-solvers (i.e., nominal teams).

After demonstrating the beneficial effect of managing resources applied to engineering design teams, a preliminary analysis into this process management is done. This analysis involves tracking the evolution and motivation of these interventions throughout the experiment. The general pattern emerging is an exploratory-to-convergent managerial strategy. Overall, managers seem to promote a breadth of search within the design space early on in the ideation process, resulting in more novelty and uniqueness in the solutions. Near the end ideation, management is used to help teams think about the engineering specifications and requirements of the design problem, and to refine search, as closure is brought to the process. Furthermore, managers also help their teams maintain cohesion in their thought, as measured by the semantic similarity of the teams' discourse.

There could be a number of different explanations of why the unmanaged teams did not perform better than individuals, and taken alone, these results are not sufficient to provide any complete explanation. However, one of the main differences between team collaboration and independent problem-solving is the role of verbalization. Thus, in an attempt to begin answering this question of the possibility that verbalization acts as a cognitive barrier to problem-solving, an appendage to the current study is run, where participants individually solve the same conceptual design problem, but this time, while simultaneously verbalizing their ideas out loud. Results show that verbalization does not act as a direct deterrent to problem-solving, as those individuals who think aloud generate solutions of nearly equal quality compared to those individuals who problem-solve silently. Future work can identify other potential obstacles to team problem-solving, as, at least in conceptual design, verbalization does not seem to be a factor.

The title of this paper raises the question of whether engineers are better off working alone. This work supports the claim that they are, at least, in the domain of conceptual design. The empirical results from this work expand growing evidence that individuals are more effective than teams in a variety of problem-solving situations, including conceptual design (Gyory et al. 2018b). Ultimately, the hope is to understand why teams are not always maximally proficient, in what types of circumstances they significantly underperform, and what methods are most effective in assisting them. This study is a step towards uncovering approaches and methods that can build more focused and efficient engineering design teams, which have major implications for how design teams work together and solve problems in practice.

Acknowledgements This work was supported by the Air Force Office of Scientific Research (AFSOR) under Grant nos. FA9550-16-1-0049 and FA9550-18-1-0088. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors. Portions of this work were presented at Design, Computing, and Cognition Conference 2018 and ASME International Design and Engineering Technical Conference 2018.

References

Agogué M, Kazakçi A, Hatchuel A et al (2014) The impact of type of examples on originality: explaining fixation and stimulation effects. J Creat Behav 48:1–12. https://doi.org/10.1002/jocb.37

Alnuaimi OA, Robert LP, Maruping LM (2010) Team size, dispersion, and social loafing in technology-supported teams: a perspective on the theory of moral disengagement. J Manag Inf Syst 27:203–230

Bellamy L, Evans DL, Linder DE, McNeill BW, Raupp G (1994) Teams in engineering education. Report to the National Science Foundation on Grant Number USE9156176, Arizona State University, Tempe, AZ

Brooks LR (1968) Spatial and verbal components of the act of recall. Can J Psychol Can Psychol 22:349–368

Brun J, Ezzat H, Weil B (2015) Managing the impacts of non-verbal devices on idea generation: a new challenge for creative leaders. European Academy of Management-EURAM, Varsovie

Cicchetti DV (1994) Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychol Assess 6:284–290. https://doi.org/10.1037/1040-3590.6.4.284

Comer DR (1995) A model of social loafing in real work groups. Hum Relat 48:647–667. https://doi.org/10.1177/001872679504800603

Diehl M, Stroebe W (1987) Productivity loss in brainstorming groups: toward the solution of a riddle. J Pers Soc Psychol 53:497–509. https://doi.org/10.1037/0022-3514.53.3.497

Dong A (2005) The latent semantic approach to studying design team communication. Des Stud 26:445–461. https://doi.org/10.1016/j.destud.2004.10.003

Dong A, Hill AW, Agogino AM (2004) A document analysis method for characterizing design team performance. J Mech Des 126:378. https://doi.org/10.1115/1.1711818

Dutson AJ, Todd RH, Magleby SP, Sorensen CD (1997) A review of literature on teaching engineering design through project-oriented capstone courses. J Eng Educ 86:17–28. https://doi.org/10.1002/j.2168-9830.1997.tb00260.x

Ezzat H (2017) Leader for creativity: modelling and experimenting defixation-oriented leadership, Doctoral dissertation, PSL Research University

Ezzat H, Camarda A, Cassotti M et al (2017) How minimal executive feedback influences creative idea generation. PLoS One 12:1–11. https://doi.org/10.1371/journal.pone.0180458

Ezzat H, Agogué M, Weil B, Cassotti M (2018) Specificity and abstraction of examples: opposite effects on fixation for creative ideation. J Creat Behav. https://doi.org/10.1002/jocb.349

Faure C (2004) Beyond brainstorming: effects of different group procedures on selection of ideas and satisfaction with the process. J Creat Behav 38:13

Fu K, Cagan J, Kotovsky K (2010) Design team convergence: the influence of example solution quality. J Mech Des 132:111005. https://doi.org/10.1115/1.4002202

Girotra K, Terwiesch C, Ulrich KT (2010) Idea generation and the quality of the best idea. Manag Sci 56:591–605. https://doi.org/10.1287/mnsc.1090.1144

Goldschmidt G, Casakin H (1999) Expertise and the use of visual analogy: implication for design educatio. Des Stud 20:153–175

Goucher-Lambert K, Moss J, Cagan J (2018) A neuroimaging investigation of design ideation with and without inspirational stimulidunderstanding the meaning of near and far stimuli. Des Stud. https://doi.org/10.1016/j.destud.2018.07.001

Gyory JT, Cagan J, Kotovksy K (2018a) The effect of managerial intervention on engineering design team performance. In: Gero J (ed) Design computing and cognition'18. Como, Italy

Gyory JT, Cagan J, Kotovsky K (2018b) Should teams collaborate during conceptual engineering design? An experimental study. In: ASME International Design Engineering Technical Conference. Quebec City, Canada

Harman D (1986) An experimental study of factors important in document ranking. In: SIGIR'86 Proc 9th Annu Int ACM SIGIR Conf Res Dev Inf Retr, pp 186–193. https://doi.org/10.1145/253168.253206

Hey J, Linsey J, Agogino a M, Wood KL (2008) Analogies and metaphors in creative design. Int J Eng Educ 24:283–294

Hoffman LR (1965) Group problem solving. In: Berkowitz L (ed) Advances in experimental social psychology, vol 2. Academic Press, New York, pp 99–131

Hsi S, Linn M, Bell J (1997) The role of spatial reasoning in engineering and the design of spatial instruction. J Eng Educ 151–158

Isaksen SG (2013) Facilitating creative problem-solving groups. http://www.cpsb.com/research/articles/creative-problem-solving/Facilitating-CPS-Groups.html. Accessed 12 Dec 2017

Janis IL (1972) Victims of groupthink: a psychological study of foreign-policy decisions and fiascoes. Houghton Mifflin, Oxford

Jansson DG, Smith SM (1991) Design fixation. Des Stud 12:3–11. https://doi.org/10.1016/0142-694X(91)90003-F

Jones PE, Roelofsma PHMP (2000) The potential for social contextual and group biases in team decision-making: biases, conditions and psychological mechanisms. Ergonomics 43:1129–1152. https://doi.org/10.1080/00140130050084914

Karau SJ, Williams KD (1993) Social loafing: a meta-analytic review and theoretical integration. J Pers Soc Psychol 65:681–706

Kavadias S, Sommer SC (2009) The effects of problem structure and team diversity on brainstorming effectiveness. Manag Sci 55:1899–1913. https://doi.org/10.1287/mnsc.1090.1079

Kim MS (2007) Analysis of team interaction and team creativity of student design teams based on personal creativity modes. In: Proc ASME 2007 Int Des Eng Tech Conf Comput Inf Eng Conf 1–13. https://doi.org/10.1115/DETC2007-35378

Landauer T, Foltz P (1998) An introduction to latent semantic analysis. Discourse Process 25:259–284. https://doi.org/10.1080/01638539809545028

Laughlin PR (2011) Group problem solving. Princeton University Press, Princeton

Lee CS, Huggins AC, Therriault DJ (2014) A measure of creativity or intelligence? Examining internal and external structure validity evidence of the remote associates test. Psychol Aesthetics Creat Arts 8:446–460. https://doi.org/10.1037/a0036773

Linsey JS, Tseng I, Fu K et al (2010) A study of design fixation, its mitigation and perception in engineering design faculty. J Mech Des 132:041003. https://doi.org/10.1115/1.4001110

Linsey JS, Markman AB, Wood KL (2012) Design by analogy: a study of the wordtree method for problem re-representation. J Mech Des 134:041009–041009. https://doi.org/10.1115/1.4006145

Liu S, Boyle IM (2009) Engineering design: perspectives, challenges, and recent advances. J Eng Des 20:7–19. https://doi.org/10.1080/09544820802670914

Liu YC, Bligh T, Chakrabarti A (2003) Towards an "ideal" approach for concept generation. Des Stud 24:341–355. https://doi.org/10.1016/S0142-694X(03)00003-6

Maier NR (1967) Assets and liabilities in group problem solving: the need for an integrative function. Psychol Rev 45

McComb C, Cagan J, Kotovsky K (2015a) Rolling with the punches: an examination of team performance in a design task subject to drastic changes. Des Stud 36:99–121. https://doi.org/10.1016/j.destud.2014.10.001

McComb C, Cagan J, Kotovsky K (2015b) Lifting the veil: drawing insights about design teams from a cognitively-inspired computational model. Des Stud 40:119–142. https://doi.org/10.1016/j.destud.2015.06.005

McComb C, Cagan J, Kotovsky K (2017) Optimizing design teams based on problem properties: computational team simulations and an applied empirical test. J Mech Des 139:041101. https://doi.org/10.1115/1.4035793

Mills JE, Treagust DF (2003) Engineering education—Is problem-based or project-based learning the answer. Aust J Eng Edu 3(2):2–16

Mittal S, Frayman F (1989) Towards a generic model of configuration tasks. In: IJCAI Proceedings of the 11th international joint conference on artificial intelligence, vol 2. pp 1395–1401

Moss J, Kotovsky K, Cagan J (2011) The effect of incidental hints when problems are suspended before, during, or after an impasse. J Exp Psychol Learn Mem Cogn 37:140–148. https://doi.org/10.1037/a0021206

Myers DG (1976) The group polarization phenomenon. Psychol Bull 83:602–627

Putman VL, Paulus PB (2009) Brainstorming, brainstorming rules and decision making. J Creat Behav 43:23–39

Rickards T, Moger S (2002) Creative leadership processes in project team development. Br J Manag 11:273–283. https://doi.org/10.1111/1467-8551.00173

Rietzschel EF, Nijstad BA, Stroebe W (2006) Productivity is not enough: a comparison of interactive and nominal brainstorming groups on idea generation and selection. J Exp Soc Psychol 42:244–251. https://doi.org/10.1016/j.jesp.2005.04.005

Schmidt A (2013) Groupthink. Britannica Online Academic Edition. Encyclopædia Britannica, Inc. Retrieved from https://www.britannica.com/contributor/Anna-Schmidt/9345859

Seat E, Lord SM (1999) Enabling effective engineering teams: a program for teaching interaction skills. J Eng Educ 88:385. https://doi.org/10.1109/FIE.1998.736842

Shah JJ, Smith SM, Vargas-Hernandez N (2003) Metrics for measuring ideation effectiveness. Des Stud 24:111–134. https://doi.org/10.1016/S0142-694X(02)00034-0

Siggelkow N, Rivkin JW (2005) Speed and search: designing organizations for turbulence and complexity. Organ Sci 16:101–122. https://doi.org/10.1287/orsc.1050.0116

Sio UN, Kotovsky K, Cagan J (2015) Fixation or inspiration? A meta-analytic review of the role of examples on design processes. Des Stud 39:70–99. https://doi.org/10.1016/j.destud.2015.04.004

Sio UN, Kotovsky K, Cagan J (2018) Silence is golden: the effect of verbalization on group peformance. J Exp Psychol Gen 147(6):939

Stempfle J, Badke-Schaub P (2002) Thinking in design teams—an analysis of team communication. Des Stud 23:473–496. https://doi.org/10.1016/S0142-694X(02)00004-2

Taylor DW, Berry PC, Block CH (1958) Does group participation when using brainstorming facilitate or inhibit creative thinking? Adm Sci Q 3:23. https://doi.org/10.2307/2390603

Tesluk PE, Quigley NR, Tekleab AG (2009) A longitudinal study of team conflict, conflict management, cohesion, and team effectivenss. Gr Organ Manag 34:170–205

Thompson G, Lordan M (1999) A review of creativity principles applied to engineering design. Proc Inst Mech Eng Part E J Process Mech 213:17–31. https://doi.org/10.1243/0954408991529960

Turkalj Z, Fosic I, Dujak D (2008) Conflict management in organization. Interdiscip Manag. https://doi.org/10.1080/03050629708434896

Wielinga B, Schreiber G (1997) Configuration-design problem solving. AI Des 49–56

Yilmaz S, Seifert C (2010) Cognitive heuristics in design ideation. In: 11th Int Des Conf Des 2010 1–11

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.