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# Triangulation of Indicators of Successful Student Design Teams*

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*This paper reports on research conducted on design teams at UC Berkeley over several years at the undergraduate and graduate levels. The paper provides a triangulation of indicators of successful design teams drawn from different research methods. The research sources include questionnaires, team documents, email communication, individual design journals, faculty evaluations, and ratings from external design judges. Computational linguistic algorithms are used to analyze the text documents with a focus on latent semantic analysis and semantic coherence. Sketches are analyzed using a comprehensive list of metrics, including Shah's 'variety' measure for quantifying the breadth of the solution space explored during the generation process. A synthesis of the results provides interesting and counterintuitive indicators for predicting the success of student design teams. This analysis, in turn, provides insight into learning how the student design teams negotiate and learn the design process and can assist educators in improving the teaching of design.*

**Keywords:** design teams; shared understanding; semantic coherence; latent semantic analysis; sketching

## INTRODUCTION

DESIGN EDUCATION provides a valuable platform for integrating theory and practice in academic engineering programs. It also helps develop students' socio-technical skills in teamwork, communication and the evaluation of social impact of technology as highlighted by the ABET general engineering criteria [9, 10, 27]. Although engineering educators strive to provide design students with the optimum learning experience, the nature of design and product development makes it difficult to gauge intermediate progress, in terms of cognitive understanding and learning. Often it is only with the end result of a project that the design team's performance can be measured. Unfortunately, for educators and student design teams it is then too late to provide meaningful interventions. Design teams are challenging to study due to their multifaceted characteristics, all acting to produce complex relationships and social processes from which a design eventually emerges. The instructor's window into the process is through shared documents and observations of team dynamics during limited class or studio time slots. Consequently, it is very difficult to observe what is actually happening within these multi-functional design teams when they are in the process of designing. This makes it difficult to develop a deep understanding of how students learn in complex design settings.

We have used multiple research methods performed over several semesters on new product development classes to try and improve the window the instructor has on student learning during the design process. Peer evaluation surveys play the largest role for this purpose; however, other retrospective analyses have also been used to provide insight into potential interventions or signals during the learning process. These studies provide insight into useful indicators of successful, and unsuccessful, student design teams, including the social relationships within the teams that typically lie hidden to the educator.

The focus of this paper is to synthesize the results of these prior studies across these different dimensions [8, 13–14, 22–23] and combine with new insights provided by an analysis of the peer evaluation surveys. In doing so we draw together and compare the indicators of successful design teams provided by each, to enable us to understand better how the students learn to design and what factors translate into the output of successful design products.

## RESEARCH METHODS

Design classes afford both rich learning and research environments. By instrumenting [4] student design activities and student performance, instructors have the opportunity to understand better students' integrative thinking and design skills [3, 7, 10]. Many studies in design research have used student designers as subjects. Leifer's research team pioneered research into the use of computational text analysis to understand communication and team processes [16] and to measure design creativity using noun phrases extracted from documents [19]. Other studies have identified effective educational practices by studying the various processes used to teach design and develop students' design skills and knowledge [1–3].

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The general approach to our research involves the capture of documents generated within a design team working on a collaborative design project: mission statements, customer surveys, concept descriptions, concept selection rationale, prototype description and test plans, and design evaluation, as well as design sketches. According to the data source type we used one of the following research methods: (1) computational linguistics on text documents, (2) protocol analysis on sketches, and (3) web based surveys filled out by the student designers. These methods are described in more detail below.

*Computational linguistics—Latent semantic analysis*

Product design is a social activity characterized by information exchange and negotiation [5, 9]. At the heart of this social activity is the development of a shared understanding of the design problem. Landauer's Latent Semantic Analysis (LSA) [15] presents a means of evaluating and comparing documents for differing levels of semantic coherence as a proxy for shared understanding. LSA is a text analysis method that extracts the meaning of documents by applying statistical analysis to a large corpus of text to detect semantic similarities. The underlying theory for LSA is that by looking at the entire range of words chosen in a wide variety of texts, patterns will emerge in terms of word choice as well as word and document meaning. LSA is chosen as an analysis tool for the student teams' text documents and written communication because of its demonstrated success in identifying contextual meanings of documents, and for analyzing the cognitive processes underlying communication [15].

*Protocol analysis of sketches*

Sketches are the medium whereby designers explore their thoughts, reflect on their actions, and externalize their design thinking. Many researchers have performed verbal protocol studies of designers to understand problem solving in design [24]. Goldschmidt [12] postulates that design protocols should include not only verbalization but also drawing components. She proposes the use of sketching activities as visual thinking and imagery as a conceptual framework for investigation. Our study uses retrospective protocol analysis of design documents to study sketches generated by product design teams in their design process.

*Peer evaluations*

A team's beliefs about their capacity to work efficiently and well together has been termed 'collective efficacy' by Lent *et al.* [17]. Interventions may be necessary to aid teams with negative feelings of 'collective efficacy' however it is difficult for an educator to observe and identify teams who may be struggling in this way. In order to understand better these subjective experiences and perceptions of student team cohesion, communication, productivity and team dynamics we employed extensive peer evaluation surveys in the form of web-based questionnaires. The surveys were completed by the design teams at the middle and end points of the design process and provided process insights that would have been difficult for the instructors to observe directly.

*Test-beds*

Two project-based new product design courses at the University of California at Berkeley provided the primary test beds for this paper: (1) ME110, a senior level undergraduate design course in the department of mechanical engineering and (2) ME290P, a multidisciplinary graduate design course. The ME110 class is almost entirely undergraduate mechanical engineering students; the ME290P class is a mix of graduate students with about a third from business, a third from engineering disciplines, and a third from the industrial design program at the California College of the Arts in San Francisco. A few additional graduate students from information management, architecture and biology take the course as well. While the ME110 students typically have no previous product development experience the ME290P class often has a range of prior experiences. Each class typically has from 10 to 15 product development projects with groups of 4–5 students. In contrast to ME110, teams in the graduate class are deliberately composed of students from each of the disciplines present. These two different types of design teams provided a comparison for the study of design activities. The analysis focus areas for each test bed are provided in Table 1. The text used in both courses was Ulrich and Eppinger [25], which advocates a stage gate framework similar to that in Cooper 1990 [6].

*Semantic coherence and shared understanding*

Agogino's research group at UC Berkeley has used LSA to evaluate design team performance over the last four years. They build their research program on the hypothesis, supported by studies

Table 1. Focus areas for each of the test beds

| Focus of Study | ME110 Year 1 | ME110 Year 2 | ME290P Year 1 | ME290P Year 2 | ME290P Year 3 |
|---|---|---|---|---|---|
| Shared understanding | | | ✓ | ✓ | ✓ |
| Sketching | ✓ | ✓ | | ✓ | ✓ |
| Peer evaluations | | | | | ✓ |

from industry [7], that performance of multi-disciplinary, cross-functional engineering design teams strongly influences successful new product development. They hypothesize that the written expressions of design concepts captures the 'mental model' or 'shared voice' of the design team. Hill *et al.* [13] used LSA to analyze the text documents for latent semantic content created by the teams throughout the course of the design process. This technique was able to identify a shared 'voice' of the designers using topical similarity within the textual content of their documents. The underlying hypothesis was that topical similarity and shared voice are indicators of a 'shared frame of reference of the design process.' In their paper they suggested that the same technique could be applied for both detecting and diagnosing teams that are functioning poorly.

This work was continued in greater depth in Hill *et al.* [14] using LSA to study the documents from a number of design teams from one of the product development courses. The results of the study provided a degree of quantitative evidence suggesting that a higher degree of shared understanding and cohesiveness within design teams correlated with a better process and design quality outcome. The final performance evaluation in all of the design studies is based on a comprehensive combination of instructors' grades and ratings by panels of external professional designers.

These studies all performed analyses of the overall semantic coherence of design team documents averaged over the entire semester. However, the potential of the tool to provide insight during the course of the semester remained unstudied. Song *et al.* [22] aimed to study the variation in shared understanding of design teams over the course of the design process using the stage gate design model in Cooper [6]. The design documents were analyzed to test whether patterns of semantic coherence variation over time also correlated with design performance. The semantic coherence of the teams was measured as it varied document by document and within email communication over the course of the design process of the design teams.

Figure 1, from our previous study in Song *et al.* [22], shows the variation of semantic coherence of two representative design teams over the design stages—Team B, a high performing team, and Team C, a lower performing team, in the second year study of ME290P. Each point represents the semantic coherence between two consecutive documents. Thick lines indicate the average coherence for each stage. We can see that Team B maintains a high level of average semantic coherence throughout the process, but with high levels of cyclic variation within each stage. In spite of this cyclic variation, Team B seems to end each stage at a relatively high level. This coherence or ability to communicate a shared understanding at the end of each stage is reflected in the high mark given by the faculty and external judges at the end of class. Team C with a poor faculty/judge mark for their project, on the other hand, shows less cyclic variation in coherence; the team started with low semantic coherence, increased their average coherence during stage two, but eventually ended up with a diverged 'story' at the end.

Overall, this document analysis study establishes a formal methodology for providing a real-time window into the design process and coherence of design thinking of the teams. Empirical evidence proved that patterns of semantic coherence variation over time correlates with design outcomes. Recognition of such patterns enables appropriate intervention to promote focused design behavior and thinking.

*Conclusions of shared understanding study*

Results from this study provided important insights on the characteristics of semantic coherence

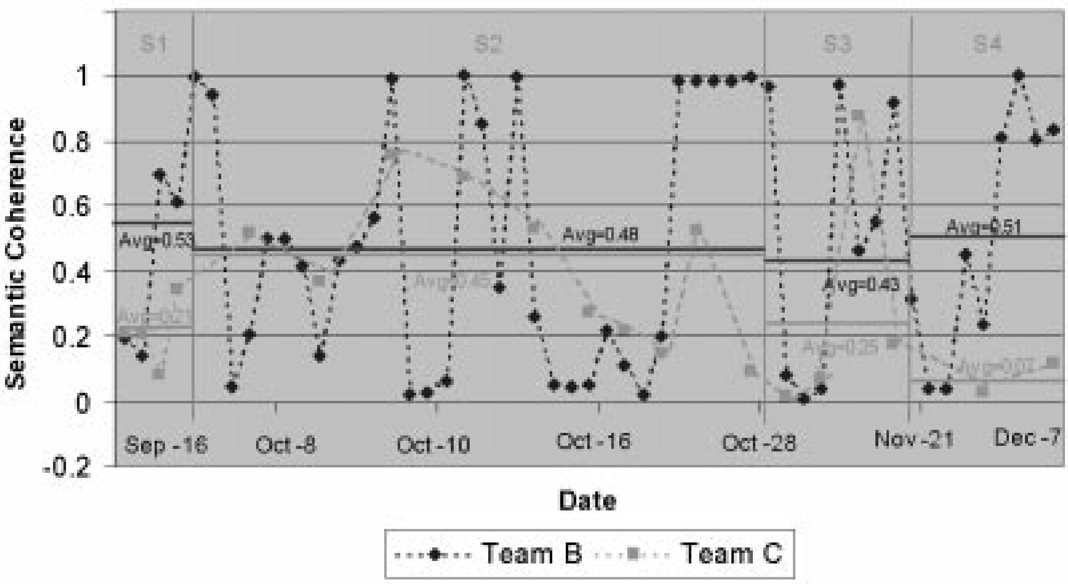


Fig. 1. Variation of semantic coherence of two teams.

in the design process as well as several useful indicators for successful design teams based on metrics and patterns associated with semantic coherence.

- These studies suggest that product design teams should reflect on their own performance by examining patterns of shared understanding during the design process rather than at the end.
- The design process is characterized by an iterative broadening and narrowing of design possibilities, and an iterative reconciliation of design interests and conflicts towards a set of shared agreements.
- The occurrence of increasing coherence, or shared understanding, with cycles of divergence during the design process is desirable. In contrast, the situation of decreasing average coherence in design is likely to be disruptive and increasingly dysfunctional.
- Higher overall semantic coherence across the overall design process correlates with improved design outcomes.
- High performing teams are more likely to have high variation in shared understanding during the early design stages.
- High semantic coherence and shared understanding is desirable towards the end of the design process.
- The total number and frequency of email communication does NOT provide any indication of high performing design teams.

## SKETCHING BEHAVIOR

Written text, in both email communication and design documents, is an important means of communication for designers. However, designers are often very visual people and a great deal of communication between group members concerning the product is through product sketches. Sketching allows communication of many features that would be almost impossible to convey using text, or even voice alone. A more complete understanding of the design process therefore requires an analysis of the role of sketching [18, 28].

In order to understand better this additional facet of communication between designers Song *et al.* [23] reported empirical studies of student designers' sketching activities in new product design teams. This study utilized protocols for analyzing design sketches from student design journals in two consecutive years. The study also developed a comprehensive set of metrics for characterizing and evaluating design sketches: generation, type, medium, representation, annotation, variety, and level of detail. It is shown how these metrics afford a greater understanding of the design process. Different types of sketches are found to be associated with different design stages and statistically significant correlations between some types of sketches and the performance of product design teams are identified.

The study also analyzed the conceptual design sketches submitted as team deliverables. These sketches are different 'design' solutions for a single concept direction. The variety measure (Shah *et al.* [21]) was applied to provide a quantitative score to show the broadness of the design team in exploring the solution space. Shah recommends examining how each design function is satisfied in order to measure variety. Figure 2 illustrates how the conceptual origins of a group of ideas are analyzed through a genealogical categorization based on how ideas fulfill each design function. The nodes in the tree carry the count of ideas in each category at each level and the number of branches gives an indication of the variety of ideas.

*Conclusions from sketching analysis*

This study provided the following insights into the role of sketching in the design process as well as useful indicators of good design outcomes:

- Variety is an indicative measure as to how well designers explored the design solution space.

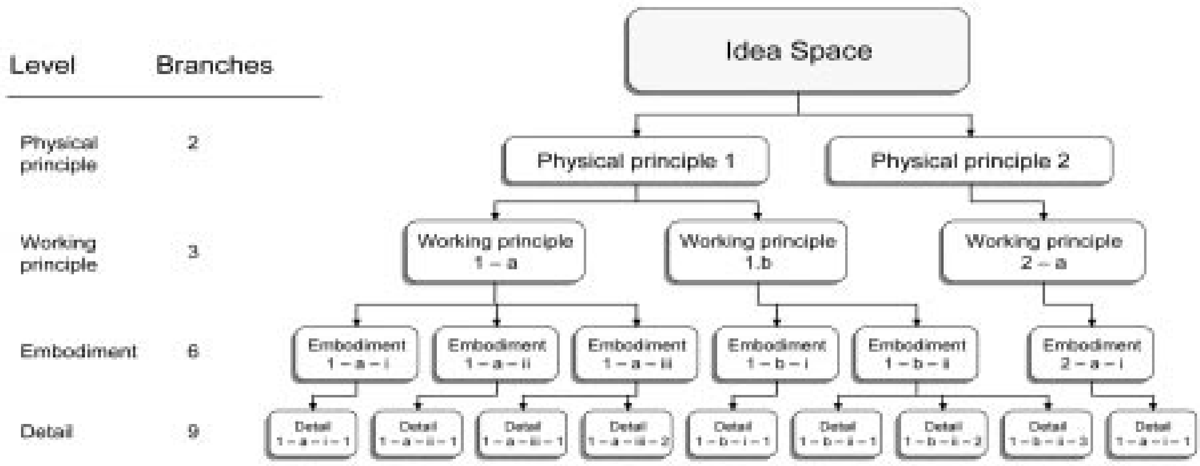


Fig. 2. Illustration of genealogical categorization for *variety* measure.

- The volume of total sketches and the number of three-dimensional sketches has an increasingly positive effect on the design outcome as the design proceeds from preliminary investigation, through conceptual design, to detailed development and testing.
- An increasing number of sketches with higher levels of detail towards the later design stages correlate with a higher design outcome. This is most likely due to the influence of a well-developed design. Similarly, there was a positive correlation between greater number of three-dimensional and two-dimensional multi-view sketches in the later design stages.
- A statistically significant multi-correlation reveals that the combination of high quantity and variety of product concepts is related to a high project ranking. This suggests that the combination of high quantity and variety of product concepts increases the likelihood of a good design outcome.
- There was a strong correlation between the variety measure of a team's sketches and their performance at the midterm stage. However, there was no significant correlation found between the team's variety measure in the early design stages and the final design outcome

## PEER EVALUATIONS

The primary data sources for the team self-assessment analyses were in the form of an on-line questionnaire administered twice during the semester: at the midterm point and at the end. The questionnaires required the students to provide evaluations of the performance of the team, themselves and the other designers in their team The midterm evaluations were used primarily as a channel of anonymous feedback within the teams to enable them to gauge their progress and the social relationships within the team. The questionnaires helped the students identify and reflect upon sources of conflict within the team and how they had, or could be, resolved. In this respect the midterm evaluation is an integral part of learning the design process.

The questionnaires also provide the educators a valuable window into the workings of the design teams. The instructors can use the feedback and their experience to identify teams that need advice or coaching on resolving conflicts within their team. Though instructors may discuss the presence of a conflict with the students, it is the students who must resolve it. The questionnaires contained questions on a wide range of issues, including: perceived sharing of work; level of conflict; productivity; progress towards a common product view; attitudes towards the team; team communication; cohesiveness and concept generation; information needs, sources and distribution methods; individual ratings of members attitudes and work; conflicts encountered; team members' overall performance and role; leadership roles; lessons learned; and team performance goals. The final peer evaluation questionnaire also asks the students about the role and success of the design coaches in supporting and guiding the teams.

In the context of this triangulation study the responses to the following question concerning a common product view were analyzed:

How well did your team progress towards a common product view shared by all team members?

a) We had strong general agreement on the product definition and direction.
b) We had general agreement although a few outstanding issues remained unanswered.
c) Product definition was mostly clear but lack of general 'buy-in' by all team members.
d) Product definition remained unclear; strong disagreements between team members.

For this question we looked at the responses of the midterm and final evaluations. Each response was given a numerical rating (using d as the lowest

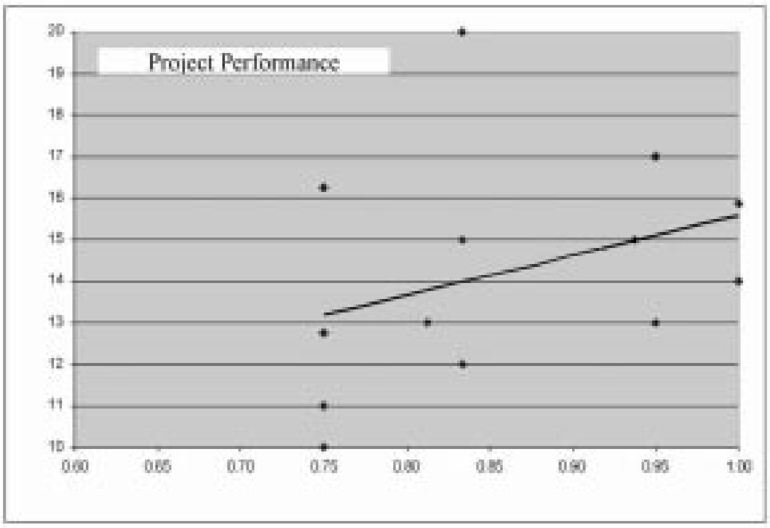


Fig. 3. Performance and common product view.

Table 2. Spearman rank coefficients for common product view (statistically significant values in bold)

| Teams in statistical pool | Midterm | Final | Change | Average |
|---|---|---|---|---|
| All teams | 0.00 | **0.47** | 0.36 | 0.38 |
| Removal of outlier | 0.30 | **0.62** | **0.53** | **0.55** |

and a the highest) so that a higher team score represented a stronger shared product view. We analyzed the normalized absolute values at the midterm and final evaluations, the overall level given by the average of the two responses, and the change, positive or negative, between the two evaluations. We calculated Spearman rank correlations with the final performance of the product teams. We also studied the trend coefficients and r-squared values for other possible correlations.

*Conclusions of peer evaluation analysis*

Figure 3 shows a scatter plot of product team performance on the vertical axis against a quantitative conversion of the teams' responses to the question. Each point represents a single team in the study. The graph illustrates a statistically significant correlation for progression of higher performing teams towards a common view of the product in the final stages of the design (Spearman rank coefficient of correlation is 0.47 for the final ranking). Interestingly, the highest performing team in the study had a high level of conflict throughout the process. With early warning from the midterm peer evaluation and instructor intervention, the team was able to re-channel conflict energy into constructive product activities, resulting in high ratings from the external judges. If this team is considered an outlier and removed from the analysis, the Spearman rank correlation between common product view and final ranking rises to a statistically significant value of 0.62. As shown in Table 2, there were no statistically significant correlations with the midterm ranking (row 1 the case where all of the teams are considered and row 2 the case with the outlier removed). This indicates that the midterm feedback to the team and instructor intervention had a positive effect on the final team performance.

## TRIANGULATION OF STUDIES

The results from synthesizing the data and conclusions from the three research methods, computational linguistic, protocol analysis of sketches and peer evaluations, provide a triangulation of indicators of successful design teams. In general, the number and detail level of sketches and document content reflect a design team's successful progress in the design process. The results drawn from data on sketches, email and documents corroborate each other. Figure 4 summarizes the trends, indicating that successful design teams reveal similar patterns of sketching activities and shared understanding as the design proceeds. It is clear that as the design progresses from the preliminary stage through refinement to detailed design, good design teams show increasing semantic coherence with decreasing variation as well as a marked increase in the level of detail and explicitness of the drawn material that is produced; that is the drawing moves from unstructured sketches of varied concepts to more precise and explicit drawn representations as design teams gradually reach shared understanding on the design problem and design solutions overtime.

The likelihood of design team success also increases when the variety of early concepts is high. The synthesis of results shows that the 'variety' measure, a reasonable indicator of the exploration of the design space, correlates well with the variation of semantic coherence in earlier design stages. Our study demonstrates that successful design teams start with a high variety of concepts and high variation of semantic coherence. A thorough exploration of alternatives early in the product design process greatly reduces the likelihood that the team will stumble upon a superior concept late in the product design process; large semantic variation and high variety of concepts are

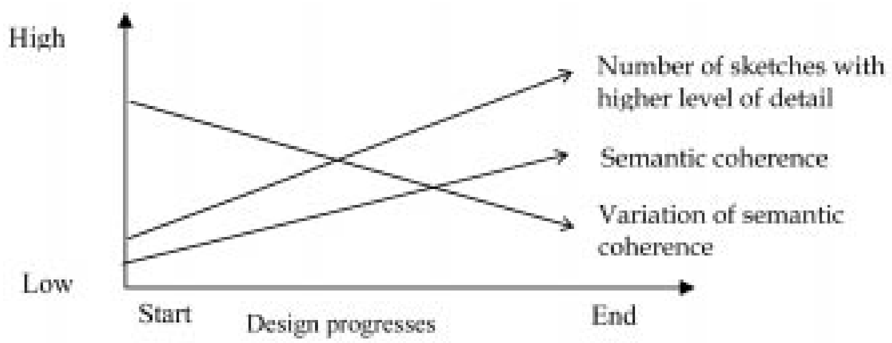


Fig. 4. Trends of semantic coherence, variation of semantic coherence, and number of sketches with higher level of details for high performing design teams.

early indicators of potential good design outcomes later in the design process.

In triangulating the results of the sketching and text analysis studies with the peer evaluations we find additional insights. Notably, a high-performing team's perception of a high shared definition of the product at the end of the process is correlated with success and mirrors the increase in detail and dimensionality of the team's sketching behavior and also greater semantic coherence, as evidenced from their documents and communication they produce.

In addition, while it is desirable to increase the shared definition of the product as the project progresses, it is also desirable to have a general strong agreement on the definition throughout the process, especially at the end of critical stage gates. This parallels the finding by Dong *et al.* [8] that a greater overall shared understanding is desirable and, from the sketching study, that a greater number and greater detail of sketches correlates with higher performance [23]. The increase in the shared definition of the product could be explained, as a team with a lower initial shared definition will explore a wider range of concepts to converge on the best solution.

## CONCLUSIONS

Research along a number of different axes has provided different indicators of successful design teams. Importantly, the research methods combined objective and subjective measures for triangulation. These indicators can be used as guides to help identify aspects of high-performing teams and in many cases their inverses can be used by educators to identify poorly performing teams. However, identification alone is just the start of providing a better learning experience for student design teams. To improve this experience, identification must be followed by appropriate intervention by an educator. These indicators are also valuable in guiding educators in their decision of when not to intervene as much as when they should.

It is not necessarily true that a high-performing team corresponds to greater student learning; much can be learned from our mistakes and failures as well as from our successes. Nevertheless, a high-performing design team is typified by teams that have successfully negotiated the multiple tasks and stages of the design process and may result in greater satisfaction and enjoyment from the final outcome.

One of the key conclusions from this triangulation is simply that encouraging design teams to monitor their activities can be beneficial. Monitoring the variation in their design thinking and the progress in their sketches, as well as their individual perceptions of team dynamics and product definition are all important potential indicators of a team's eventual outcome. By being sensitive to these aspects a team can actively adapt their activities to address any potential weaknesses by asking questions like: Are we too focused when we should be expanding our scope? Have we been thoroughly exploring the design spaces? We are experiencing conflict but is it healthy or disruptive?

*Assistance for Educators*

Other than helping the students themselves, below we offer some recommendations for educators based on the results of the triangulation study to help improve the students' learning experience.

The LSA analyses showed that 'shared understanding' as measured by LSA 'semantic coherence' was significantly correlated with design team performance. Counter to prevailing thinking in the design research community, high performing teams did not gradually increase semantic coherence over the design process; rather they were punctuated with high variability in semantic coherence within stage gates and only moved to high coherence at the end of each stage gate when deliverables were due. Low performing teams were characterized by both low levels of average coherence and infrequent cycles of 'lows' and 'highs' in coherence.

1. While it is important for teams to come to a shared vision through communication before stage-gates, allow and encourage maximum exploration during design stages.
2. Encourage teams to iterate by diverging at each stage-gate in terms of different perspectives and opinions and variety of concepts considered.
3. Encourage and provide for sketching activity in general and as a method of communication for the team.
4. Monitor the level of detail in sketching as an indication of progress and a common product definition.
5. Do not take a high volume of email to be indicative of either student learning or team progress, as it has only a minimal effect on performance.
6. Recognize that even high performing teams 'experienced some levels of strife' (Dong *et al.* [8]). Early conflict can be a sign that a team is fully exploring the space and airing their views.
7. Take advantage of peer evaluations as a window into the team dynamics and team progress. Use them to encourage communication within teams and warn against too early convergence on a concept. The evaluations also allow students to act on any issues, increasing their learning experience [20].

*Future work*

We intend to increase the strength of our findings by repeating the studies on future semesters of design classes and to explore additional variables such as psychometric tests including the Meyers–Briggs Temperament Indicator [11, 26], discipline and gender. We also intend to expand the analyses on the peer evaluations to cover perceptions of work distribution, effectiveness of concept generation and concept selection methods, and anecdotal accounts of conflicts encountered and team experiences.

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