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Using Latent Semantic Analysis (LSA) to Study Expert Design Team's Verbal Communication

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SUMMARY

Teams of people design products. They bring their own language, experiences, perspectives, and detailed knowledge to the design. Thus, design in a team can be regarded as a social process of reaching a “shared understanding”, through activities such as information exchange, compromise and negotiation. Latent Semantic Analysis (LSA) is a computational linguistic technique. It is well known for its ability of modeling human knowledge representations and capturing the latent relations between words and passages. LSA was applied in design team research. Previous research showed that by mining design teams’ formal documentation, LSA can successfully capture different designers’ semantics. Quantification metrics used to measure semantic coherence of design documentation could predict successful design outcomes.

This research focuses on the verbal communication in design teams and aims to develop assessment tool(s) that can be used to enhance the communication in design teams. This study expands the previous LSA-based design team communication framework by decoupling the design process from the design outcome. Moreover, a new quantification metric is proposed to complement existing metrics. Data from two experimental studies were used to examine our postulations. The results showed that LSA is able to capture the semantics of different design team members’ verbal communication. The semantic coherence of a design team is more correlated to design process quality than design outcome quality.

Chapter 1: Introduction

1.1 Background

Today, teams of people design. The benefit of design teams lies in their ability to integrate different designers' experiences, perspectives and detailed knowledge. Thus, design in a team can be regarded as a social process of reaching successful agreements, through activities such as information exchange, compromise and negotiation (Citera et al., 1995).

Studies of collaborative design teams include social cognition, psychometrics, sociometry, computational linguistic analysis and so on. Despite the different disciplinary roots, researchers in these areas are all inspired by one question - why does one design team succeed whereas others fail?

Cognitive scientists study social cognition in design teams by investigating the social activities such as information exchange, compromise and negotiation among team members. One common method used by them is observation. This is a way to gather data without asking questions to the respondents and at the same time to record their natural behavior (Sekaran, 1984). In design teams, designers must communicate their thoughts to others, thus communication offers a fairly direct path to the thinking process of designers. The widely adopted method is verbal protocol analysis, which converts the "think aloud" transcripts into data (Ericsson & Simon, 1993). Studies of design team communication using protocol analysis can lead to interesting insights into

the thinking behaviors of design teams, such as the strategies for reaching shared understanding (Valkenburg & Dorst, 1998) and the patterns of basic cognitive processes in design teams (Stemple & Badke-Schaub, 2002).

Besides the study of social cognition, some researchers have addressed the question on how to compose a high performance team from individuals who are placed on teams. There is a wide body of research on the use of psychometric measures, such as Myers-Briggs Temperament Indicator (MBTI), which may be used to analyze and predict the behaviors and the likelihood of success of a team (Barrick, Stewart, Neubert, & Mount, 1998; Reilly, Lynn, & Aronson, 2002). The basic idea behind the personality test approach is to match people either with similar personality or with different personalities. The advantage of a group of people with comparable personality is that they will be more compatible and able to work together efficiently, while the purpose to match people with dissimilar personalities is to produce a heterogeneous group that will generate different ideas or approaches reflecting the different personalities of the group members. These techniques have been successfully applied to form engineering design teams. Wilde (2000) applied Jungian Typology and MBTI to the formation of student engineering design teams. By forming teams consisting of members with complementary roles, a plurality of viewpoints, a neutral manager and a “wild card”, the likelihood of a successful design outcome increased.

An alternative measurement tool called sociometry, may provide predictive power regarding team performance. This is a technique for mapping the relationships of

attraction and rejection among members of a team. Using sociometry, one can determine the degree to which individuals are accepted in a group. Lucius & Kuhner (1997) used sociometry to predict team performance in the work place and found that sociometrically dense teams are both more satisfied with their intra-team relations and more productive.

The research mentioned above has led to an improved understanding of design teams. The problem though is that the methods (e.g., protocol analysis, psychometric evaluations, sociometry) are typically inaccessible to design teams and design team managers or they rely on surveys and interviews before the design activity starts. For sure, the methods have limited use for evaluating the impact of communication interactions, and for improving the design process in real time.

Computational text analysis is a relatively new method for studying design teams. Mabogunje & Leifer (1997) explored the relationship between design creativity and the number of noun phrases design teams generated in the conceptual design stage. They extracted noun phrases from transcripts of design team meetings and found that the number of unique noun phrases generated is directly correlated to a higher level of creativity, though not necessarily successful outcomes.

Lately Dong and his colleagues used Latent Semantic Analysis (LSA) to assess the performance of design teams (Dong, 2004, 2005; Dong, Hill, & Agogino, 2004; Hill, Dong, & Agogino, 2002). LSA is a computational linguistic techniques, and it can

measure the semantic similarity between words and texts (Landauer, Foltz, & Laham, 1998). It is nearly automatic and permits rapid analysis of a large number of design documentations or conversations. This capability allows it to complement the aforementioned protocol analysis and psychometric techniques, and creates the potential to embed design assessment techniques into design environments to measurably enhance the communication of design teams.

1.2 Research Motivation

Hill, Dong, & Agogino (2002) explored the relationship between design document textual coherence, team cohesiveness, shared understanding, and process and design outcome quality as shown in Figure 1. This can be considered as a framework for studying team communication based on LSA. They asserted that textual coherence is both an indicator and measure of team coherence, which subsequently, indicates the level of shared understanding of the team. Moreover, teams with a high level of shared understanding will exhibit both high design process quality and high design outcome quality.

Figure 1 Relationship between Document Coherence, Team cohesiveness, Shared Understanding and Design Outcomes (Hill et al., 2002)

Based on the framework, Dong, Hill, & Agogino (2004) studied the connection between coherent design documentation and successful engineering design outcomes. To quantify the semantic coherence of the design documentation they proposed two metrics based on LSA and found a positive correlation between the semantic coherence and the design outcomes.

Dong (2004) expanded the research to analyze team members' verbal communication during design. He identified that the two metrics which were used to characterize semantic coherence of design documentation are not appropriate to analyze conversations. This was because the team members' conversations were less structured than formal documentation and tended to be "noisy". Hence, he suggested another method by computing the average semantic coherence between utterances which were one utterance away, two utterance away, and so forth. The underlying idea was that

there should be an orderly mapping between semantic coherence and distance between utterances. Two metrics based on the method were proposed to characterize the semantic coherence. However, the two newly proposed metrics were unable to quantify the level of coherence of the conversation and to correlate themselves to successful outcomes as had been done for design documentation.

In a later study, Dong (2005) introduced the “knowledge convergence” method to compute how an individual’s language use becomes similar to the group’s overall language. He stated that the method indicates, as a conservative assertion, an acquisition of common semantics, and with a bolder interpretation, the acquisition of a socially held representation of a design artifact. Dong (2005) suggested that the team’s “concept centroid” represents the team’s common semantics as well as the shared representation of the design artifact, while each member’s “concept centroid” represents his or her own semantics and representation of the design artifact. The expansion of the “concept centroid” from the whole team to each team member provides the opportunity to investigate the semantics of team members and creates the potential to propose new quantifying metric to characterize the semantic coherence of the team’s verbal communication.

Hill, Dong, & Agogino (2002)’s framework offers a guideline to study the relationships between team communication and design process quality as well as design outcome quality. Researches based on this framework generated some good results.

Nevertheless, the study of teamwork on military teams suggests the necessity to measure processes and outcomes separately. In their review work, Paris, Salas, & Cannon-Bowers (2000) stated that process and outcome measures complement one another and they provide a complete picture of team performance. Successful outcomes demonstrate the team objectives have been met. On the other hand, a focus on how the task was accomplished is important for diagnosing performance problems that may prevent desired outcomes. Because flawed processes occasionally result in successful outcomes, it is necessary to measure both if one is to ensure consistently effective performance. Although the remark is drawn from study on military teams, it provides a guideline to study teamwork in general. Table 1 shows the team performance measure proposed by Cannon-Bowers & Salas (1998).

Table 1 Team Performance Measure (Cannon-Bowers & Salas, 1998)

<i>Team Performance</i>	
Process	Outcomes
<ul style="list-style-type: none"> • Information exchange • Communication • Supporting behavior • leadership 	<ul style="list-style-type: none"> • Mission effectiveness • Aggregate latency and accuracy

Furthermore, the literature of design creativity study exhibits the importance and significance of creativity for successful design outcomes. Due to the emotional nature of creativity, it rarely comes with standard processes. This means a design team with

good communication, supporting behavior, information exchange and so forth, may end up with an ordinary design.

The abovementioned reasons motivate us to decouple design process quality and design outcome quality. Adopting from Hill, Dong, & Agogino (2002)'s framework, we suggest that design process and design outcome should be decoupled as shown in Figure 2. Moreover, we speculate that design teams' communication coherence is more correlated to design process than design outcome.

Figure 2 Decoupling of Design Process and Design outcome

1.3 Research Objectives and Scope

There are three objectives in this research.

1. To examine whether LSA can capture the semantics of different design team members. This premise was taken for granted in the previous study on design

team's verbal communication (Dong, 2004, 2005). Although it was shown that LSA can capture the semantics of different people's formal design documents (Hill, Song, Dong, & Agogino, 2001), it is worth to investigate whether it works in the case of verbal communication, for the language use in formal documentation and verbal conversation is known to be fairly different.

2. To propose new metrics besides the "language and knowledge convergence" metrics. If LSA is able to capture the semantics of different design team members, we can compute the similarity and semantic coherence between different members can be computed, which indicates the level of shared understanding between team members.
3. To explore the relationship between semantic coherence and design process quality, between semantic coherence and design outcome quality separately. To examine whether design teams' verbal communication coherence is more correlated to design process than design outcome.

This study is based on analysis of the verbal communication during the design process. It does not take into account the non-verbal expressions, such as drawings and gestures that the design team members may use in the process.

1.4 Organization of the Report

The report consists of five chapters. Chapter 1 presents the background of the study and discusses a variety of research on design team. This is followed by a statement of research motivation. After that, three research objectives are proposed and presented, followed by the research scope. Chapter 2 provides a comprehensive literature review of related research and studies, including design cognition, differences between novices and experienced designers, design creativity, design team communication, and latent semantic analysis (LSA) in design studies. In chapter 3, the methodology of this research is presented. At first, the LSA approach in this study is illustrated. After that, Design of the two experimental studies are explained. In chapter 4, the results from the two experimental studies are reported. Based on the results, we discuss how these results meet the research objectives. Chapter 5, the last chapter, summarizes the

achievements in addressing the objectives, states the limitation in this research and suggests the future study in using computational linguistic techniques to analyze design team's communication.

Chapter 2: Literature Review

This chapter provides a comprehensive literature of topics, which are related to this research. It starts with a review of research on design cognition, followed by an examination of differences between novice and experienced designers. Studies on design creativity are then reviewed. After that, various research on design team communication is summarized. An introduction of LSA is presented, followed by its application on design team study.

2.1 Design Cognition

Research in design cognition address one basic problem: how designers deal with design problems? There are three distinctive paradigms: prescriptive, empirical (descriptive) and design-as-an-art.

Research on prescriptive design primarily focuses on design methodology, aiming to give structure to design (Hubka & Eder, 1988). Examples of studies include the work of Pahl & Beitz (1984, 1995), Hubka & Eder (1992) and Suh (1990). This body of work derives from a rational analysis of design tasks and their requirements and has yielded systematic approaches to designing in architecture, engineering and product design. Pahl & Beitz's Total Design (1984, 1995) and Hubka & Eder's Systematic Approach (1992) addressed the sequence of phases and steps in the design process. They both structured the design process into main phases: (1) Clarification of the task (2) Conceptual design (3) Embodiment design and (4) Detail design. Suh (1990) presented a design methodology that is known as Axiomatic Design (AD), which conceptualizes design activity as "a continuous interplay between what we want to achieve and how we want to achieve it". It utilizes matrix methods to systemically transform customer needs into functional requirements, design parameters, and process variables. AD offers a systematic approach, which is particularly well suited to design problems in ergonomics (Helander, 2001).

Empirical studies of design activity have shown that designers, in practice, rarely use systematic design methodologies as described in the normative theories. Gunther & Ehrlenspiel (1999) compared the design processes of designers who had university education or design education with designers who had not received education in design methodology at a university. The results showed that design methodology as a rigid prescription does not work even under ideal conditions in laboratory situations. In a subsequent study, Ehrlenspiel (1999) stated the prescriptive theory of design neglects many specific factors and constraints that designers need to cope with in their daily work, such as economic constraints and time pressure. Guindon (1990) investigated the problem-solving skills of designers and found that an opportunistic decomposition is better suited to handle the ill-structuredness of design problems in the early stages of design. Rasmussen, Pejtersen, & Goodstein (1994) suggested that an actual design task cannot be represented by a prescriptive sequential progression from problem formulation to solution. Instead, they recommended a more realistic approach based on separate, yet compatible, representations of the knowledge domains involved in the design task and of decision strategies and heuristics used for navigation in these domains.

Research on the design-as-an-art has revealed that the design process simply cannot be grasped by any methodology (Schön, 1983). Instead, the work of designers is pretty much the same as the work of artists who apply different kinds of methods in a flexible manner using a process of “appreciation, action and re-appreciation”, constantly updating on his own work (Roozenburg & Dorst, 1998).

Despite the extensive contributions to the design literature and design practice stemming from research on these approaches, shortcomings exist in accounting for the relationships between design practice and the designer. For instance, the prescriptive approach isolates design methodology from their wider context (Rasmussen et al., 1994; Stemple & Badke-Schaub, 2002). It simply prescribes a method without considering what designers actually do. The shortcoming of the empirical approach is that it is not always theory-based; hence, the empirical research approach sometimes lacks a clear direction (Stemple & Badke-Schaub, 2002). The design-as-an-art theory is considered a revolution in design research, but much of the research is suffering from “romanticizing” design. Moreover, a significant drawback in accepting the design-as-an-art approach is that in doing so, the door is essentially closed for any effort to model and investigate collaborative design performance (Okudan & Rao, 2005).

2.2 Differences between Novices and Experienced Designers

Only recently have researchers begun to study the differences between how novices and experts approach problems where constraints and context are ill-defined. Design is well known as an ill-structured and ill-defined problem, since many possible solutions exist for one design problem, however, there are no clearly defined rules to obtain these solutions (Cross & Cross, 1997; Goldschmidt, 1997).

Several studies (Ericsson & Charness, 1997; Waldron & Waldron, 1996; Zeitz, 1997) examined the reasoning skills that novices and experts utilize in engineering design. The results showed that novice designers had a tendency to reason backwards and to use a deductive approach. Experts, on the contrary, tended to reason forwards, and to combine forward and backward reasoning when facing more complex problems.

Waldron, Jelinek, Owen, & Waldron (1987) studied the amount of information a designer can store in a single “chunk” in his working memory and found that experienced designers held larger amount than novice designers. Kavalki and Gero (2001) carried out a protocol analysis of an expert and a novice. They found that the expert’s cognitive activity and productivity was approximately three times higher than that of the novice designer. They suggested that this may be because of different ‘chunking’ of processes by the novice and expert. Research conducted by Gobert (1999) found that experienced designer have better spatial memory than novices.

Ahmed, Wallace, & Blessing (2003) examined how novice and experienced designers approach design tasks. Their findings showed clear differences between novice and experience designers. In particular, novice designers rely largely on trial and error. Experienced designers use particular design strategies such as ‘refer to past designs’, ‘question data’, and ‘aware of trade-offs’, which Novice designer were unaware of.

2.3 Design Creativity

Cooper (1996) indicated that new product development is a vital endeavor for modern industries. Companies must learn how to innovate effectively, overhaul their new product processes—from idea to launch—and incorporate winning ideas for successful new products. As the first step in the innovation process (Majaro, 1988), the generation of ideas or ‘creativity’ is critical to the success of the new product and thus inspired researchers from different disciplines such as design theory, management, economics and so forth.

Heap (1989) explained that creativity is the synthesis of new ideas and concepts through radical restructuring and re-association of existing ones’, whereas innovation is the implementation of the results of creativity. It is still one of the most mysterious elements in human thinking.

Some of the researchers from design theory proposed certain procedures with the intention that they will enhance creativity in design. Krohe (1996) presented a view on managing creativity as well as a summary of 22 creativity stimulating techniques, such as bug listing, goal/wish, manipulative verbs, nominal group technique, wildest idea, wishful thinking and so on. Cross (1997) constructed a procedure based on a ‘creative-leap’ example and generic descriptive models of creative design to provide further insight into the example. Lugt (2000) described four creative problem solving experiments involving meetings in which graphic variations on brainstorming

technique were explored. Dorst and Cross (2001) proposed refinements to the co-evolution model, and also suggested that creativity in the design process can validly be compared to 'burst of development'. These techniques are universally employed for encouraging creativity and assisting people in producing a wide variety of novel ideas.

Besides the rather cognitive view of design creativity, other researchers believe that design creativity has a strong emotional component. There are hence good reasons to be critical to many of the propositions mentioned above (Finke, Ward, & Smith, 1992).

An important minority of pioneering design theorists has implied that the most valuable part of the design process is what occurs inside the designer's head and partly out of reach of his conscious control (Jones, 1992). In his book 'Emotional Design: Why We Love (or Hate) Everyday Things', Donald Norman (2004) stated that design is driven by a rich set of associations which is coupled to a rich set of emotions. Creativity is not a logical undertaking, but driven more by emotional processes. Helander (2006) described that good design is created by designers with extensive experience and knowledge and by individuals who possess certain cognitive abilities, which makes it easier to design. Individuals with long experience and knowledge have a greater base for associations, which is necessary for creative design.

2.4 Design Team Communication

Verbal communications and visual representations are primary tools used by design team members in cooperative activities (Lawson & Loke, 1997). Research specifically addressing communication during the design process can be classified into four categories based on their research approach: retrospective, component, progressive, and combinatory (Sonnenwald, 1996), see Table 2. Most of the research is based on data from actual design participants during software as well as engineering design.

Table 2 Research on Communication during the Software and Engineering Design Process

Research focus	Author(s)	Communication focus	Research method(s)	Research data
Retrospective	(Curtis, Krasner, & Iscoe, 1988)	Communication breakdown	Structured interview	Interview data
	(Peng, 1994)	Communication in terms of common images and models	Case histories	Artifacts and reports
	(Kraut & Streeter, 1995)	Communication networks	Survey	Survey data
Component	(Guinan, 1986)	Interpersonal communication techniques	Protocol analysis and performance survey	Interview data
	(Walz, 1988)	Conflict and behavior roles	Protocol analysis	Videotaped recording of meetings among software team members
	(Olson, Olson, Cater, & Storosten, 1992)	Time spent in meeting activities	Protocol analysis	Video recording of meetings with designers and developers
Progressive	(Minneman, 1991)	Communication techniques and purpose of communication	Observation and protocol analysis	Videotaped recording of engineering project teams
	(Song, Dong, & Agogino, 2003)	Time variation of textual coherence	Computational linguistics	Design documentation
	(Dong, 2004; Hill et al., 2002)	Textual coherence of design documentation	Computational linguistics	Design documentation
	(Dong, 2005)	Coherence of verbal communication	Computational linguistics	Videotaped recording of engineering project teams
Combinatory	(Sonnenwald, 1996)	Communication roles	Observation, document analysis, interview, survey	Interview data, survey data, project documentation
	(Khalid, 2004)	Visual collaborative communication	Observation, Protocol analysis, survey	

Research in the ‘retrospective’ category examines retrospective and historical accounts of the design process by asking the design participants to describe the communication activities and histories of the design process retrospectively. In this way, these studies analyze communication using participants’ reconstruction of their realities. Examples of studies that have taken this approach include the work of Curtis, Krasner, & Iscoe (1988), Peng (1994), and Kraut & Streeter (1995).

Curtis, Krasner, & Iscoe (1988) studied the problems of designing large software systems by conducting one-hour-long structured interviews with 97 designers and developers from nine corporations involved in 19 projects in stages ranging from early planning to maintenance. They reported the three most salient problems in design for the designers and developers were: the superficial knowledge of the application, fluctuating and conflicting requirements, and communication and coordination breakdowns. Factors influencing communication breakdowns included communication skills of individuals, existing incentive systems, different representational formats, rapid change, local jargon, breakdown of information capture, and cultural norms for individual behaviors.

Peng (1994) explored communication in collaborative design from the perspective of cooperative architectural modeling. He analyzed three cases of architectural modeling and proposed that there were two important conditions for communication: first, the participation and coordination among heterogeneous systems of representation and action that individual members of a design team work with; and second, the

interconnection between common goals shared by all participants and domain-oriented goals pursued by individuals. In exploring how the conditions were met, he found that it was useful to characterize communication in terms of the interrelations between common images shared by the group and domain design expressions known by individuals. Peng suggested that design team members create artifacts by representing, mapping, constructing and querying these images and expressions.

Another retrospective study surveyed the inter-group coordination practices across 65 projects within a corporation to discover how designers and developers communicated and coordinated software development. Kraut & Streeter (1995) found that extensive interpersonal networks appeared to improve design outcomes, especially in projects with a high degree of uncertainty. Design situations with denser cross-boundary networks were better informed and coordinated, and the use of formal procedures did not seem to improve inter-group coordination.

The second category of studies was termed ‘component’. These studies focused on components, or phases, of the design process, and thus view a ‘slice’ of communication behavior during the design process. Guinan (1986) investigated communication during requirement interviews between software designers and users (in laboratory settings) and its relationship to designers’ performance. She proposed that several interpersonal communication techniques, such as meta-communication, reframing and backtracking, are positively related to designers’ performance.

Walz (1988) also focused on the early phases of the design process but studied intra-group communication among designers. She analyzed conversations of 17 meetings attended primarily by designers over four months during the software requirement specification stage of an object-oriented database management system. Walz observed conflict and uncertainty in these meetings and suggested that conflict among designers was high as they attempted to determine design requirements, but decreased when they communicated the determined requirements to users, and increased again as they discussed how to fulfill the requirements.

Olson, Olson, Cater, & Storrosten (1992) expanded Walz's study by analyzing 10 design meetings from four software teams. Similar to Walz, they carried out a protocol analysis of videotaped meetings but focused on the time spent in meeting activities. They found similar patterns across design teams. In meetings, teams spent only 40% of the time in direct discussions of design, with swift transitions between alternative ideas and their evaluation. Thirty percent of meeting time was spent taking stock of their progress, and coordination activities consumed approximately 20% of the time. Clarification of ideas across these activities took one-third of the time, indicating that participants spent a large amount of time sharing and explaining their expertise.

Studies in the 'progressive' category investigate the design process as it evolves over time. For example, research by Minneman (1991) investigated communication across multiple design phases. In particular, Minneman observed engineering teams, analyzed video recordings of team interaction, and intervened in the design process by sharing

his insights into their communication with design team members. Minneman suggested that the practices of negotiating understandings, conserving ambiguity, tailoring engineering communication for recipients, and manipulating mundane representations were important strategies used by design participants. Song, Dong et al (2003) adapted computational linguistic techniques to study the variation in textual coherence of design documentation between design stages and found the occurrence of increasing textual coherence with cycles of divergence during the design process was desirable. In the subsequent studies, they investigated the relationship between design outcomes and coherence of design team communication (Dong, 2004, 2005; Hill et al., 2002). The results showed two forms of design team communication - formal documentation and verbal communication; both were positively correlated to design outcomes.

The research reported by Sonnenwald (1996) incorporated aspects of the retrospective, component and progressive research approaches to identify the communication roles during the design process. It studied a design project over 14 months using multiple methods such as unstructured interviews, observation, document analysis, sociometric surveys, and critical incident interviews. Sonnenwald found 13 communication roles that emerged during design situations: sponsor, inter-organizational star, intra-organizational star, inter-group star, intra-group star, inter-task star, intra-task star, inter-disciplinary star, intra-disciplinary star, interpersonal star, mentor, agent, and environmental scanner. Khalid (2004) reported how a real world concurrent engineering team collaborated online. The study showed the team's real world collaborative behavior was naturally transferred online. Despite the well claimed

shortcomings of computer-mediated interaction, it tends to obscure status differences, resulting in greater participation by team members.

2.5 Latent Semantic Analysis

Latent Semantic Analysis (LSA) is a theory and a method for capturing and analyzing the similarity of words and text passages by statistical computations applied to a large corpus of text (Landauer & Dumais, 1997). The baseline theory of LSA is that the aggregate of all the word contexts in which a given word appears or does not appear provides a set of mutual constraints that largely determines the similarity of meaning of words and sets of words to each other (Landauer et al., 1998).

The similarity estimates derived by LSA are not simple co-occurrence counts, but are based on Singular Value Decomposition (SVD), which is capable of correctly inferring much deeper relations within text passages. Singular Value Decomposition (SVD) is closely analogous to factor analysis. LSA believes that the choice of dimensionality in which all of the local word-context relations are represented can be of great importance and that reducing the dimensionality - the number parameters by which a word of passage is described, from the number of initial contexts to a much smaller number will often produce much better approximations of human cognitive relations. It is this dimensionality reduction step, that surface information is captured into a deeper abstraction and the latent relationship between words and passages is revealed (Landauer et al., 1998).

LSA has been applied to a wide range of problems for identifying the contextual meanings of words and documents, including information retrieval (Dumais, 1994; Foltz, Kintsch, & Landauer, 1998), assessing learning (Landauer, Laham, & Foltz, 2000; Shapiro & McNamara, 2000), modeling knowledge acquisition (Landauer & Dumais, 1997), identifying shared understanding in design (Hill et al., 2001), characterizing design team performance (Dong et al., 2004) and predicting team performance on simulated military mission (Martin & Foltz, 2004). The application of LSA in design team study will be reviewed in detail in section 2.4.

An example has been used in several publications to demonstrate how LSA works (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990; Landauer & Dumais, 1997; Landauer et al., 1998). This report will use it as well to illustrate what the technique can accomplish. Since it is for illustrating purpose, the log-entropy transformation is skipped in the example.

This example uses the titles of nine technical memos as text passages, shown in Figure 3 Example of Nine Text Passages (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990). The first five are about human-computer interaction (HCI), and the last four are from mathematical graph theory.

Example of text data: Titles of Some Technical Memos	
c1:	<i>Human machine interface for ABC computer applications</i>
c2:	<i>A survey of user opinion of computer system response time</i>
c3:	<i>The EPS user interface management system</i>
c4:	<i>System and human system engineering testing of EPS</i>
c5:	<i>Relation of user perceived response time to error measurement</i>
m1:	<i>The generation of random, binary, ordered trees</i>
m2:	<i>The intersection graph of paths in trees</i>
m3:	<i>Graph minors IV: Widths of trees and well-quasi-ordering</i>
m4:	<i>Graph minors: A survey</i>

Figure 3 Example of Nine Text Passages (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990)

Unique words which appear at least twice are extracted from the text passages. There are twelve words: human, interface, survey, user, computer, system, response, times, EPS, trees, graph, and minors. Therefore, the word-by-document matrix consists of twelve rows and nine columns as shown in Figure 4. Each cell contains the number of time each unique words appearing in the corresponding text passage.

	c1	c2	c3	c4	c5	m1	m2	m3	m4
human	1	0	0	1	0	0	0	0	0
interface	1	0	1	0	0	0	0	0	0
computer	1	1	0	0	0	0	0	0	0
user	0	1	1	0	1	0	0	0	0
system	0	1	1	2	0	0	0	0	0
response	0	1	0	0	1	0	0	0	0
time	0	1	0	0	1	0	0	0	0
EPS	0	0	1	1	0	0	0	0	0
survey	0	1	0	0	0	0	0	0	1
trees	0	0	0	0	0	1	1	1	0
graph	0	0	0	0	0	0	1	1	1
minors	0	0	0	0	0	0	0	1	1

Figure 4 Word-by-document Matrix of the Nine Text Passages (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990)

The word-by-document Matrix is subject to SVD and the resulting three component matrices are shown in Figure 5. Multiplying the three matrices will perfectly reconstruct the original matrix. Please note that different notations were used for the component matrices. In section 3.4 notations U and V^T were used, where $U=W$ and $V^T=P'$.

Figure 5 Three Component Matrices after SVD (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990)

Figure 6 shows the approximation of the original word-by-document matrix by using the first two scaling factors in the diagonal matrix S , shown as circled columns in Figure 5. Each value in this new representation has been computed as a linear combination of values on the two retained dimensions

	c1	c2	c3	c4	c5	m1	m2	m3	m4
human	0.16	0.40	0.38	0.47	0.18	-0.05	-0.12	-0.16	-0.09
interface	0.14	0.37	0.33	0.40	0.16	-0.03	-0.07	-0.10	-0.04
computer	0.15	0.51	0.36	0.41	0.24	0.02	0.06	0.09	0.12
user	0.26	0.84	0.61	0.70	0.39	0.03	0.08	0.12	0.19
system	0.45	1.23	1.05	1.27	0.56	-0.07	-0.15	-0.21	-0.05
response	0.16	0.58	0.38	0.42	0.28	0.06	0.13	0.19	0.22
time	0.16	0.58	0.38	0.42	0.28	0.06	0.13	0.19	0.22
EPS	0.22	0.55	0.51	0.63	0.24	-0.07	-0.14	-0.20	-0.11
survey	0.10	0.53	0.23	0.21	0.27	0.14	0.31	0.44	0.42
trees	-0.06	0.23	-0.14	-0.27	0.14	0.24	0.55	0.77	0.66
graph	-0.06	0.34	-0.15	-0.30	0.20	0.31	0.69	0.98	0.85
minors	-0.04	0.25	-0.10	-0.21	0.15	0.22	0.50	0.71	0.62

Figure 6 Approximation of the Original Word-by-document Matrix (Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990)

Comparing Figure 4 and Figure 6, we can note that words which occurred in some passages in the original matrix now appear with greater or lesser estimate frequency and some words which did not appear in some passages originally now do appear, at least fractionally. Examples are the two cells in rectangle for *survey* and *trees* in column m4 of Figure 4 and Figure 6. The word *trees* did not appear in this graph theory title, but because m4 did contain graph and minors, the zero entry for *trees* has been replaced with 0.66, which can be viewed as an estimate of how many times it would occur in each of an infinite sample of titles containing graph and minors (Landauer et al., 1998). On the contrary, the value 1.00 for survey, which appeared once in m4, has been replaced by 0.42, reflecting the fact that it is unexpected in this context.

To illustrate what the dimension reduction of LSA has done to relations between words and between text passages, the word-word relations and passage-passage relations are computed from the original matrix and the approximate matrix.

Word to Word Relations

Three words human, user, and minors, forming two word-word relations (human, user) and (human, minors) are used in the example. In this context, ‘minors’ is a technical term from graph theory, thus intuitively the expected result is that ‘human’ and ‘user’ are more similar than ‘human’ and ‘minors’. In the original matrix, ‘human’ never appears in the same passage with either ‘user’ or ‘minors’ – they have no co-occurrences or contiguities. The correlations (using spearman coefficient r_s to facilitate familiar interpretation) are -0.38 between ‘human’ and ‘user’ and a slightly higher -0.29 between ‘human’ and ‘minor’ as shown in Table 3. It violates the result. However, in the reconstructed two-dimensional approximation, because of their indirect relations, both correlations have been greatly altered: the human-user correlation has gone up to 0.94, and the human-minor correlation is down to -0.83. thus, because the terms ‘human’ and ‘user’ occur in contexts of similar meaning - even though never in same passage – the reduced dimension solution represents them as more similar, whereas the opposite is true of ‘human’ and ‘minors’.

Table 3 Word to Word Relations Based on Original and Approximate Matrix

	Original Matrix	Approximate Matrix
Correlation (human, user)	-0.38	0.94
Correlation (human, minors)	-0.29	-0.83

Passage to Passage Relations

The inter-correlations between each of the nine titles and all the others are computed, first based on the raw co-occurrence data, then on the corresponding vector

representing them in the two-dimensional approximate matrix. The results are shown in Figure 7.

	c1	c2	c3	c4	c5	m1	m2	m3
c2	-0.19							
c3	0.00	0.00						
c4	0.00	0.00	0.47					
c5	-0.33	0.58	0.00	-0.31				
m1	-0.17	-0.30	-0.21	-0.16	-0.17			
m2	-0.26	-0.45	-0.32	-0.24	-0.26	0.67		
m3	-0.33	-0.58	-0.41	-0.31	-0.33	0.52	0.77	
m4	-0.33	-0.19	-0.41	-0.31	-0.33	-0.17	0.26	0.56

	0.02							
	-0.30	0.44						

Correlations in two dimensional space:

	c1	c2	c3	c4	c5	m1	m2	m3
c2	0.91							
c3	1.00	0.91						
c4	1.00	0.88	1.00					
c5	0.85	0.99	0.85	0.81				
m1	-0.85	-0.56	-0.85	-0.88	-0.45			
m2	-0.85	-0.56	-0.85	-0.88	-0.44	1.00		
m3	-0.85	-0.56	-0.85	-0.88	-0.44	1.00	1.00	
m4	-0.81	-0.50	-0.81	-0.84	-0.37	1.00	1.00	1.00

	0.92							
	-0.72	1.00						

Figure 7 Inter-correlations between the Nine Titles(Deerwester, Dumais, Furnas, Lanauer, & Huarshman, 1990)

From the original matrix in Figure 4, correlations among the five HCI titles were generally low, even though all five articles were apparently about quite similar topics; half the correlations where zero, three where negative, two were moderately positive, and the average was only 0.02. The correlations among the four graph theory articles were mixed, with a moderate mean r of 0.44. Correlations between the HCI and graph theory articles average only a modest -0.30, despite the fact that they are conceptual far from each other.

In the two-dimensional approximate matrix, the topical groupings are much clearer. Most dramatically, the average correlation between HCI titles increases from 0.02 to 0.92. This happened, not because the HCI titles were generally similar to each other in the raw data, which they were not, but because they contrasted with the non-HCI titles in the same ways. Similarly, the correlations among the graph theory titles were re-estimated to be all 1.00, and those between the two classes to topic were now strong negative, with the mean $r = -0.72$.

From the above illustrations, it is observed that SVD has performed a number of reasonable inductions; it has inferred what the true pattern of occurrence and relations is for the words and the text passages if all the original data are to be accommodated in two dimensions. In this case, the inferences appear to be sensible.

2.6 LSA in Design Team Study

As mentioned in the introduction of this report, Hill (2002) explored the relationship between document coherence, team cohesiveness, shared understanding, and process and design quality outcome. They asserted that textual coherence is both an indicator and measure of team cohesiveness, which subsequently, indicates the level of shared understanding of the team. Moreover, teams with a high level of shared understanding will exhibit both high design process quality and high design outcome quality.

Following this assertion, they proposed two quantitative metrics based on LSA to measure the textual coherence and shared understanding in design teams (Dong, 2005; Dong et al., 2004). The two metrics were termed “variation in semantic choice” and “semantic coherence” shown as Equation 1 and Equation 2. Both of them were used to measure the semantic coherence of the design documentation. The lower the score of the first metric is, the higher the semantic coherence of the design documentation is; while the higher the score of the second metric is, the higher the semantic coherence of the design documentation is.

$$\sigma_i = \frac{\sqrt{\sum_{v=1}^{m_i} (S_{v,i} - C_i)^2}}{m_i} \quad (1)$$

Equation 1 Variation in Semantic Choice

$$\chi = \left\| \sum_{m_i} S_i \right\| \quad (2)$$

Equation 2 Semantic Coherence

In the equations, $s_{v,i}$ is the v -th singular vector representing a document produced by team i , c_i is the centroid of each team’s document set, and m_i is the total number of documents produced by team i . The variation in semantic choice metric indicates the closeness of each document to the average document and the semantic coherence metric measures the semantic similarity of each document.

Dong, Hill, & Agogino (2004) explored the relationship between semantic coherence and successful engineering design outcomes and suggested a positive correlation between the two. Over a 15-week period, they captured the formal documentation and emails of eight collaborative design teams. The participants were studying a graduate course in product design and development. The documentation and emails were subject to LSA. Metrics for semantic coherence using Equation 1 and Equation 2 were computed and then ordered from lowest to highest σ and highest to lowest χ to assign ordinal ranks. The performance of the design teams were ranked according to the semantic coherence as well as by two faculty members' with the assistance of a group of professional product designers and engineers. Analyses were performed for "document only," "document and e-mail," and "e-mail only". To explore the relationship, the two rank orders were subject to Spearman rank correlation to measure the extent of a direct relationship between the levels of semantic coherence of the design documentation and the quality of design outcome.

Their results showed that both measurements of the semantic coherence were positively correlated to team performance. For the design "documents only" case, the correlation was statistically significant, while only marginally significant for "documents and e-mail," and "e-mail only." It was suggested that the lower correlation associated with e-mail might be due to the large amount of noise associated with content about scheduling and administrative tasks, as opposed to project content (Dong et al., 2004).

Besides rank order correlation, another assessment was performed to predict the design team performance above or below the average (Dong et al., 2004). Team performances were separated into “above median” and “below median” according to the semantic coherence indicated by σ and χ , and the subjective assessment by faculty. The accuracy of the prediction of above or below median performance was given as Equation 3,

$$\alpha = \frac{TP + TN}{N} \quad (3)$$

Equation 3 Accuracy of Prediction

Where TP stands for the number of true positives, that is, the team was predicted to perform above median and actually performed above median; TN stands for the number of true negatives; N is the total number of teams. The accuracy of team performance prediction is 75% based on σ and χ .

Dong (2004) expanded the research on design team communication by analyzing verbal communication during design activities based on LSA. He found that the two metrics proposed for design documentation could not be applied to design team’s verbal communication. Dong suggested that this was because of the high variation in context between one utterance and the next. Instead, he proposed that the topical focus of a design conversation should be coherent and there should exist a mostly orderly relationship between semantic similarity and distance between utterance boundaries. An example of coherence vs. utterance boundaries is shown in Figure 8.

Figure 8 Log Coherence for Bamberg 1102 Team (Dong, 2004)

A 3rd degree polynomial curve was found to best fit the data (Equation 6). Based on Equation 6, two metrics - the loss of information and rate of decay were proposed. The loss of information indicates the loss of coherence using a decibel scale. C_0 represents the average coherence for adjacent utterances and c is the coherence of an utterance some utterance boundaries away. The second metric - rate of decay - measures how quickly the topic of the discussion shifts by calculating the slope of the best linear fit of the data within the incline region.

$$y = m_1x^3 + m_2x^2 + m_3x + m_4 \quad (4)$$

Equation 4 Third Degree Polynomial Curve

$$20\log\left(\frac{c}{c_0}\right) = 1dB \quad (5)$$

Equation 5 Loss of Information

Transcripts of four engineering/product design teams communicating in a synchronous, conversational mode during a design session were studied. The average coherence

between utterances which were “one” utterance away, and the average coherence between utterance which were “two” utterance boundaries away were computed and plotted. Nevertheless, the two metrics were unable to quantify the level of coherence of the conversation and correlate that to successful outcomes as had been done for communication in text. Dong suggested that rapid changes in the topic of dialog during a design discussion may not necessarily indicate an incoherent conversation. Hence, he studied the coherence of each speaker’s utterances and identified three types of conversations: constructive dialog, neutral dialog and destructive dialog. He concluded that both analytic metrics and the patterns need to be considered for verbal communication.

In his summative work, Dong (2005) reviewed the research in developing the LSA approach to study design team communication and introduced the knowledge convergence method to compute how one’s language use becomes similar to the group’s overall language. He stated that this method indicates, in a conservative assertion, an acquisition of common semantics, while in a bolder assertion, it conveys the acquisition of socially held representation of the design artifact. Both the asynchronous communication data (design documentation) and synchronous communication (transcripts of verbal communication) data from previous studies were used to illustrate the new proposed method. From the results the author concluded that knowledge convergence should happen in design teams. Moreover, the ideal knowledge tracking is characterized by Figure 9, where each speaker’s semantic coherence is closely spaced and rapid converge towards 1.

Figure 9 Knowledge Tracking for Bamberg 2302 Team (Dong, 2005)

Previous research showed that LSA could capture the semantics of different people's formal design documents (Hill et al., 2001). This premise was taken for granted in the study on design team's verbal communication (Dong, 2004, 2005). However, it is well known that the language use in formal documentation and verbal conversation are fairly different. Thus, it is worth to investigate whether LSA works in the case of verbal communication,

Also, previous studies were based on framework shown in Figure 1. That framework regarded design process quality and design outcome quality as equivalent. Experts rated each team by examining the prosocial aspects of team performance and the quality of the designed artifact the team produced. The two scores were added up to produce the team rankings, based on which semantic coherence and team quality (as a union of process and product outcome) were computed. However, as mentioned in the introduction, studies of teamwork by Cannon-Bowers and Salas (1998) suggest the

necessity to measure processes and outcomes separately. Furthermore, the literature on design creativity identifies the importance and significance of creativity for successful design outcomes (Helander, 2006; Jones, 1992; Norman, 2004). This means that a design team with good communication, supportive teamwork behavior, “free” information exchange across boundaries and so forth, may still end up with an ordinary design. These arguments motivated us to decouple design process quality and design outcome quality.

In addition, the “knowledge convergence” method (Dong, 2005) computes how an individual’s language use becomes the group’s overall language. However, it is unable to detect potential “groupthink” phenomenon. Groupthink was defined by Irving Janis (1972) as “A mode of thinking that people engage in when they are deeply involved in a cohesive in-group, when the members’ strivings for unanimity override their motivation to realistically appraise alternative courses of action.” During groupthink, a team tries to minimize conflict and reaches consensus quickly, which prevents the team from critically testing, analyzing, and evaluating ideas. In terms of LSA, what “groupthink” implies is that the semantics of each participant stays entirely identical to another colleague throughout a group situation. we propose to expand on the “concept centroid” idea proposed in (Dong, 2005) from the whole team to each team member. It provides the opportunity to investigate the semantics of team members and to propose new quantifying metric(s), which can detect “groupthink” in design teams.

Chapter 3: Methodology Development

This chapter presents the methodology developed in this research. It begins with a flowchart of the five steps in latent semantic analysis. Section 3.1 to 3.5 illustrate the detailed manipulations in each step.

Section 3.1 shows the capture of the language-based communication. Procedures of transcribing and processing the verbal communication data are then presented in section 3.2. Section 3.3 introduces how to create a word-by-document matrix and log-entropy matrix. The details of applying SVD and constructing the approximate matrix are provided in section 3.4. The method to measure the semantic coherence between team members is shown in the last section of the chapter.

The latent semantic approach in this research can be represented as the flowchart shown in Figure 10. It consists of five steps: capturing the language-based communication, transcribing and text processing, creating word-by-document matrix and log-entropy matrix, applying LSA to log-entropy matrix and constructing the approximate matrix, and finally computing semantic coherence between team members and visualizing.

Figure 10 Flowchart of Latent Semantic Approach

3.1 Capturing the Language-based Communication – Observational Study

Capturing the language-based communication is the first step in LSA analysis. In this research, LSA was only based on the verbal communication of the design team and it did not take into consideration the non-verbal communication between the design team members. Design communication of the two experimental studies was captured using video recorders. Procedures of the two studies will be presented in chapter 4.

3.2 Transcribing and Text Processing

To form the word-by-document matrix, the transcript was subject to three stages of text processing. In the first stage, the utterances which were not content-bearing, such as interjections “oh, yes”, “hmmm”, were excluded from the transcript. The remaining content-bearing utterances could consist of complete or incomplete sentences.

Second, each utterance was tagged using component words and words were analyzed in terms of noun, verb, adjective, preposition and so forth.

In the last stage additional non-content-bearing words were excluded from the transcript, including prepositions, conjunctions, exclamations, and auxiliaries. The remaining words were used to construct the word-by-document matrix which counted the frequency of occurrence of each unique word in each utterance.

3.3 Creating Word-by-document Matrix and Log-entropy Matrix

The third step is to represent the text in a matrix format as shown in Figure 11. The rows of the matrix represent all the unique words found within design team's verbal communication, and the columns stand for each individual utterance. Each cell contains the frequency of each word as it appeared in the utterance denoted by its column. The resulting matrix is referred to as a word-by-document matrix.

$$X = \begin{bmatrix} & Doc_1 & Doc_2 & \dots & Doc_n \\ Word_1 & 0 & 0 & 1 & 1 \\ Word_2 & 1 & 0 & 1 & 0 \\ Word_3 & 1 & 2 & 1 & 1 \\ \dots & 2 & 3 & 1 & 0 \\ Word_m & 2 & 0 & 0 & 2 \end{bmatrix}$$

Figure 11 Representation of Word-by-document Matrix

The word-by-document matrix is then transformed to log-entropy weights. The formula for converting can be represented as $L(i, j) \times G(i)$, where $L(i, j)$ means the local weight for term i in document j and $G(i)$ is the term's global weight over all the documents (Dumais, 1990). There are different local weightings and global weightings. The most common weighting schemes are a local log weight ($\log(freq_{ij}+1)$) and a global entropy weight (LogEntropy) (Quesada, 2007). Please note that the base of the logarithmic function in LSA is assumed to be equal to 2 (Nakov, Popova, & Mateev, 2001). The two weightings are shown in Equation 6 and Equation 7.

$$LocalWeight = \log_2(freq_{ij} + 1) \quad (6)$$

Equation 6 Local Weighting

$$GlobalWeight = 1 + \left(\frac{\sum_{1 \leq j} \left(\left(\frac{freq_{ij}}{\sum_{1 \leq j} freq_{ij}} \right) \times \log_2 \left(\frac{freq_{ij}}{\sum_{1 \leq j} freq_{ij}} \right) \right)}{\log_2 ndoc} \right) \quad (7)$$

Equation 7 Global Weight

Where $freq_{ij}$ means the number of occurrence of word i in document j and $ndoc$ is the total number of documents.

The transformation has long been known to provide marked improvement in information retrieval (Dumais, 1990; Harman, 1986). Thus the transformation step is adopted in LSA analysis in this report. The transformed matrix is called “log-entropy matrix” in this report.

A Visual Basic computer program was written to construct the word-by-document matrix and a Matlab program was written to transform the word-by-document matrix into the log-entropy matrix. The source codes of the two programs are attached in Appendix A and Appendix B, respectively.

3.4 Applying Singular Value Decomposition (SVD) and Constructing Approximate Matrix

In this step, LSA applies Singular Value Decomposition (SVD) to the log-entropy matrix. In SVD, a rectangular matrix X of dimension $m \times n$ ($m < n$) is decomposed into three matrices U , S , V^T and the matrix X is equivalent to the product of them ($X = USV^T$). Matrices $U_{m \times n}$ and $V_{n \times n}$ are the left and right singular matrices, which describes the original row entities and the original column entities respectively.

The third matrix $S_{n \times n}$ is a diagonal matrix containing descending-ordered scaling values, the number n also indicates the dimensionality of the original matrix X . It has been proven mathematically that any matrix can be so decomposed perfectly. In order to get an optimal approximation for matrix X for inferring deeper relationships, one needs to reduce the dimensionality of it. This can be done simply by keeping the first k largest scaling values and setting the remaining smaller ones to zeros in the diagonal matrix S and reproduce the original matrix by multiplying the three components matrices. The resulting matrix $\tilde{X}$ is approximately equal to X , that is, $\tilde{X} \approx X = USV^T$. The number of dimensions retained in LSA is an empirical issue. Because the underlying principle is that the original data should not be perfectly regenerated but, rather, an optimal dimensionality should be found that will cause correct induction of underlying relations, the customary factor analytic approach of choosing a dimensionality that most parsimoniously represents the true variance of the original data is not appropriate. Instead some external criterion of validity must be sought, such as the performance on a synonym text or prediction of the missing words in passages if some portions are deleted in forming the initial matrix (Britton & Sorrells, 1998).

In this research, Matlab was utilized to implement SVD and calculate the k -reduced approximate matrix. SVD is available in Matlab as a built-in function and the program to compute the k -reduced approximation was provided by Professor Andy Dong (Dong, 2007) from University of Sydney. The number of dimensions retained in LSA is an empirical issue (Britton & Sorrells, 1998) and it has to be guided by the operational

criterion of “what works best” (Dumais, 1990). Dumais (1990) tested the retrieval performance based on MED database (document abstracts in biomedicine received from the National Library of Medicine, USA) and found that the retrieval performance peaks between 70 and 100 dimensions. Previous research in design documents analysis showed that retaining dimensions 2-101 resulted in satisfactory performance (Hill et al., 2002; Hill et al., 2001). Thus in this research, we followed the conventional practice and retained dimensions 2-101.

3.5 Measuring the Semantic Coherence

Once the approximation matrix $\tilde{X}$ is produced, similarity of words and text passages can be calculated. The commonly used similarity measurement method in LSA is cosine similarity, which computes the cosine of the angle between the vector representations of the words or of the text passages.

In our study, we used two methods to study the semantic coherence to design team communication. The first one was adopted from the knowledge convergence method (Dong, 2005). In this report we name it “semantic coherence to group centroid”. The algorithm is illustrated as follows:

1. Compute the group centroid of the team by finding the average value of each row in the k-reduced matrix. The centroid is of dimension $n \times 1$.

$$C_g = \frac{\sum_{v=1}^n S_v}{n}$$

Where S_v is the singular vector representing the v -th utterance of the team and C_g represents the group centroid.

2. Extract from the K-reduced matrix the columns corresponding to each speaker and compute the centroid of each speaker.

$$C_i = \frac{\sum_{v=1}^{n_i} S_{v,i}}{n_i}$$

Where $S_{v,i}$ represents the singular vector of the v -th utterance of speaker i . i equals to the number of speakers in the team. C_i is the centroid of speaker i .

3. Compute the cosine similarity between the group's centroid and each speaker's running average centroid.

$$\cos(C_i, C_g) = \frac{C_i \cdot C_g}{\|C_i\| \|C_g\|}$$

The second method is termed “semantic coherence between team members”. It was proposed to compute the semantic coherence between any two team members. We speculated that an extremely high level of semantic coherence between team members indicates the two members’ understandings of the problem are very similar. This may result in “group think” phenomena and prevent the team from generating creative ideas. On the contrary, a low level or even negative level of semantic coherence between team members signifies that the two members are not “on the same page” at all. Hence, we postulated there exists an inverted U relationship between semantic coherence between team members and design process quality, as well as design outcome quality. The algorithm of metric two is shown below:

1. From the k-reduced dimension matrix, extract the utterances for each speaker and compute the centroid of each speaker

$$C_i = \frac{\sum_{v=1}^{n_i} S_{v,i}}{n_i}$$

2. Compute the cosine similarity between any two speakers.

$$\cos(C_i, C_k) = \frac{C_i \cdot C_k}{\|C_i\| \|C_k\|}$$

We suggest that the two coherence metrics should complement each other. Language and knowledge convergence should happen in successful design teams. At the same time, team members should feel free to share their own perspective, negotiate with fellow teammates, brainstorm to generate innovative ideas and participate equally in decision making process.

Chapter 4: Experimental Studies

This chapter describes the data collection of the two experimental studies. Section 4.1 presents the multi-disciplinary design team study conducted in a leading Asian automotive company, including subjects, task design, procedures and LSA analysis. Section 4.2 shows the collaborative product design team study conducted in China. Besides the four aspects of information following the structure of Section 4.1, this section also discusses the criteria used for the experts' evaluation.

4.1 Experimental Study One

The study was conducted to explore whether analyzing the verbal communication in design team by using LSA can capture the semantics of different members in the design team.

4.1.1 Subjects

The target group was experienced designers. The background information of the participants is shown in Table 4. All the participants were from a leading automotive company in South East Asia. The participants were selected from different departments, from manufacturing to engineering design, product styling and marketing, so that each of them could utilize and contribute their area of expertise to the design.

Table 4 Background Information of the Participants of Study One

No.	Sex	Age	Design Experience (years)	Job Title / Department
1	Female	34	6	Product Styling

2	Male	40	1	Product Planning
3	Male	45	5	Project Manager
4	Male	36	12	Product Planning
5	Male	42	8	Production
6	Male	40	17	Engineering Design
7	Male	38	1	Product Marketing

As shown in Table 4, five out of the seven participants had at least 5 years of related work experience in their current fields, except for the product marketer, who had recently transferred within the company and the less experienced product planner, who was from a subsidiary to the automobile manufacturer.

In addition, a survey to test the team members' familiarity with each other was done prior to the design task. The result of the survey indicated that all of them knew each other well. Using 7-point Likert scale to measure familiarity, the mean score was 5.44 with Standard Deviation 0.58.

4.1.2 Task design

The task was to improve the design of the current driver's seat and propose a "new and exciting" product. The product should address conventional requirements such as comfort and safety, as well as the customers' *citarasa* -- the affective needs for a specific product, driven by emotions, sentiments and attitudes (Khalid & Helander, 2004). The team was encouraged to design the seat according to the company's conventional procedures, but information on the standard three stages in product design process was provided as well, namely conceptual design, system level design and detail

design. All team members were required to contribute to the design according to their expertise and to make sure the product their team designed was consistent with the company's background. Moreover, the team was required to finish the task within two hours. For a complete description of the design task, see Appendix C.

4.1.3 Procedures

The design task was conducted in a meeting room at the automotive company. In order not to disturb the team when they designed, direct observation was not carried out. Instead, all design activities were captured using two video recorders. Before the team started, they were provided with a brief introduction of the task, followed by the presentation of the tools they could use, such as drawing papers. They were also given the written task descriptions and information on the three standard design phases. The team finished the task in 116 minutes. The outcomes of the design included

- a list of marketing requirements,
- a list of product features
- an annotated sketch of the product with specifications and detail information of the key parts
- a preliminary process flow diagram for final assembly.

4.1.4 LSA analysis

It was found that the team communicated in both English and Malay in the design task. A native Malay language speaker with technical language proficiency translated the

transcript from Malay to English where applicable. The transcript was subject to LSA analysis from step 2 to step 5. The second metric was used to compute the semantic coherence between the participants. In step two, the natural language processor POS Tagger from Stanford University was used (Toutanova, Manning, Klein, & Morgan, 2006). This tagger uses the Penn Treebank tag set (Marcus, Santorini, & Marcinkiewicz, 1993).

4.2 Experimental Study two

The data for study two was obtained from the collaborative product design team study (Qiu, 2008) from Centre for Human Factors and Ergonomics, Nanyang Technological University. The video recordings and conversation transcriptions of three experienced design teams were used to explore the relationships between semantic coherence of the team and design process quality as well as design outcome quality.

4.2.1 Subjects

The background information of the participants is shown in Table 5.

Table 5 Background Information of Participants of Study Two					
Team No.	Code	Sex	Age	Design Experience (years)	Job Title / Department
1	1-A	Male	28	6	Senior Product Engineer
	1-B	Male	28	5	Product Engineer
	1-C	Male	27	5	Product Engineer
	1-D	Female	28	5	Product Engineer
2	2-A	Male	30	5	Product Engineer
	2-B	Male	31	6	Product Engineer
	2-C	Female	28	5	Product Engineer

3	2-D	Male	33	11	Product Design Leader
	3-A	Male	28	8	Product Engineer
	3-B	Male	29	5	Product Engineer
	3-C	Male	31	6	Product Design Leader
	3-D	Male	29	6	Product Design Manager

All the participants were professional designers with at least 5 years of experience. Most of them were from leading transportation device design companies in China. All three teams were currently working design teams of their respective companies. Team members inside one team knew each other well.

4.2.2 Task design

The task consisted of three consecutive design stages, namely conceptual design, system level design and detail design. Each of the three stages lasted for two hours. The teams were asked to develop an innovative cycling device for young adults in East Asia. They were required to develop the products according to their expertise. For a complete description of the design task, see Appendix D.

4.2.3 Procedures

The study was conducted in a test room, where observers could watch without disturbing the design team's activities. Onscreen 'actions' of the designers were recorded on a monitor and a video recorder. Each team was given an introduction of the task and the tools they could use in the design. A written task description was provided.

4.2.4 LSA analysis

The three teams communicated in Chinese. Their conversations were transcribed by native speaker with technical proficiency. The transcriptions of the three product design teams' verbal communication was subject to LSA analysis following from step 2 to step 5.

4.2.5 Design process evaluation

Design process evaluation criteria in this research were built upon the team effectiveness evaluation questions suggested by Payne (2001). Eleven out of the 25 questions were chosen to assess several aspects of the team process including goal clarity, communication, information exchange and so forth. Two human factors specialists rated each team based on the 11 questions. One of the rater observed when the teams carried out the tasks, and the other one assessed their process quality by watching the video-recordings. For a complete set of evaluation criteria, see Appendix E.

4.2.6 Design outcome evaluation

Three industrial experts were invited to evaluate the design outcomes of the three design teams. They gave ratings to each team using 7-point Likert scale. Eleven assessment criteria were proposed to measure the overall design outcomes. Moreover, the experts gave assessment to the design outcome of each design stage. For a complete set of evaluation criteria, see Appendix F.

Chapter 5: Results and Discussion

The results of the two experimental studies are reported in this chapter. Experimental study one was to examine whether analyzing the verbal communication of design team by using LSA can capture the semantics of different members in the design team. To better interpret the results, it is necessary to introduce the organizational structure and the development process of the automotive company, for they are closely related to the semantic coherence results. After the introduction, measures of semantic coherences between team members are presented, followed by a discussion explaining how these results support the conclusion.

Experimental study two was to explore the relationship between semantic coherence of design teams' verbal communication and their design process quality as well as design outcome quality. Evaluation results using LSA and assessment by experts are presented and compared.

5.1 Experimental Study One: Results and Discussion

5.1.2 Organizational Structure of the Automotive Company

The organizational structure of the Asian automotive company is both horizontal and vertical.

Horizontally, whenever the company decides to develop a new model, a project team is formed, which is led by a project manager and made up by a coordinator from each department, including product planning, product styling, engineering design, product prototyping, product testing and production. These coordinators are involved in the project from the starting point till the end.

Vertically, each coordinator is either a head of a department or supervised by the head. He/She is responsible for the information exchange among different departments and within its own department.

Figure 12 shows the company's organizational structure.

Figure 12 Organizational Structure for Product Development in the Automotive Company

Note: for product marketing, besides the marketing department, there was also another sole marketing division of the firm that was responsible for building the brand name and boost car sales.

5.1.2 Development Process of the Automotive Company

The design process of the automobile company at an overview level is shown in Figure 13.

To develop a new car model there are three main phases:

- Concept development
- Design development
- Engineering & Testing development

The concept development phase begins with the concept formulation. The main actors in this stage are product marketing and product planning departments. Through the interaction with customers, and by studying styling trends and production segmentation, they try to forecast what the customers will desire several years ahead and define the product features. Following concept formulation, idea sketches are produced by the stylists using hand-drawings and computer tools such as ALIAS. After that, several 1:3 scale models are built. Upon concept approval from management, the selected concept is transferred to the next phase.

The design development phase starts with the digitizing and surface modelling using computer modelling software to create external surface (A-surface) data for the form and shape. Based on the A-surface data, a 1:1 full scale clay model is built and

presented to the management. Up to this point, the exterior of the vehicle is the only consideration. If this model is approved, a Styling-engineering Feasibility study is conducted to examine the practicality of body engineering and car internal systems installation. Meanwhile, internal surface data (B-surface) of the vehicle is created. At that point, the model is fixed and followed by the engineering and testing development phase.

After the model fix, the interior design and component design are performed by the product styling and engineering design department. Soft tooling parts are developed with specific designs and materials. The final prototype car is assemble and produced for testing. Comprehensive testing for component, material, safety, strength, and complete vehicle validates is conducted using the prototype car by the testing and homologation department. If all the testing requirements are satisfied, the vehicle is put into final production.

Figure 13 Development Process of the Automotive Company

5.1.3 Semantic Coherence in Design Team

From the brief introduction of the organizational structure and development process of the automotive company, we can see that each department works more closely with the departments which are functionally close than those which are functionally remote. For example, the product planning department works more closely with product marketing and styling department than with engineering design and production department. The functional similarity and knowledge interconnection cause similar perspectives during the process of designing an artifact. Since semantics and language use are the reflection of the internal knowledge and cognition (Pask, 1975), it is reasonable to infer that the semantics of the members who are from functionally similar departments will be more similar.

In the premise of this assertion, if LSA can capture the semantics of different members in the design team, the semantic coherence between team members derived by LSA should resemble the pattern – the semantic coherence between two team members who are from functionally similar department will be higher, while the semantic coherence between two team members who are from functionally dissimilar department will be lower.

Hence, we calculated the semantic coherence between any two team members and plotted four semantic coherence graphs to show the coherence between a team member from certain department and his or her team mates from all the other departments.

Table 6 shows that the highest semantic coherence happens between product marketer and product planner, which is up to 0.70 and the lowest is between stylist and production engineer, which is only 0.24. Moreover, Table 6 shows that the semantic coherence between stylist and all the other participants is relatively low, none of which was above 0.35. This is because the stylist was busy drawing and was seldom involved in the discussion during the whole design activity. She only spoke 18 utterances. Since LSA analysis is based on the communication of the design team, we decided that the data from the stylist was not appropriate and excluded in the data analysis.

Table 6 Semantic Coherence between Participants from Different Departments

	Product marketer	Product Planer	Stylist	Engineering Designer	Production Engineer	Project Manager
Product marketer	1	0.70	0.30	0.57	0.39	0.55
Product Planer	0.70	1	0.33	0.57	0.35	0.57
Stylist	0.30	0.33	1	0.25	0.24	0.29
Engineering Designer	0.57	0.57	0.25	1	0.42	0.53
Production Engineer	0.39	0.35	0.24	0.42	1	0.39
Project Manager	0.55	0.57	0.29	0.53	0.39	1

Figure 14 to Figure 17 show the semantic coherence between a member from one particular department and the other team members from different departments. To better illustrate the changes of coherence, the semantic coherence of the member with himself or herself is included. It is marked as 1 in the graph.

The x-axis shows the different departments in the automobile company, following its organizational structure. The index for each department is: 1-product marketing, 2-product planning, 3-stylist, 4-engineering design, 5-product prototyping, 6-product testing, and 7-production. The difference between any two indices can be considered as the functional distance between the two departments. For instance, the functional distance between product marketing and product planning is 1, and that between product marketing and engineering design is 3.

The design task involved only participants from five departments: product marketing, product planning, styling, engineering design, and production. In addition, the stylist was excluded from the data analysis due to the reason mentioned before. Therefore, there are four points in each graph. They explain the semantic coherence between a team member and himself as well as between the other three team members.

5.1.3.1 Semantic Coherence between Product Marketer and Other Team Members

Figure 14 Semantic Coherence between Product Marketer and Other Team Members
(Department index: 1- product marketing, 2-product planning, 3-styling, 4-engineering design, 5-product prototyping, 6-product testing, 7-production)

Figure 14 shows the semantic coherence between the product marketer and the product planner, the engineering designer and the production engineer. The coherence decreased steadily as the product marketer and the other members became more functionally apart and less dependent. In addition, the semantic coherence between the product marketer and the product planner was fairly high. This indicates the active interaction between him and the product planner.

5.1.3.2 Semantic Coherence between Product Planner and Other Team Members

Figure 15 Semantic Coherence between Product Planner and Other Team Members
(Department index: 1- product marketing, 2-product planning, 3-styling, 4-engineering design, 5-product prototyping, 6-product testing, 7-production)

From Figure 15, it is observed that the product planner used more similar semantics with the product marketer whose department was right next to product planning. The semantic coherence dropped to 0.57 with the engineering designer who was two departments away. The product planner used quite different language with the production engineer, which was pointed out by the low coherence of 0.35.

5.1.3.3 Semantic Coherence between Engineering Designer and Other Team Members

Figure 16 Semantic Coherence between Engineering Designer and Other Team Members
(Department index: 1- product marketing, 2-product planning, 3-styling, 4-engineering design, 5-product prototyping, 6-product testing, 7-production)

The semantic coherence between the engineering designer and the other participants is shown in Figure 16. It obeys the pattern that the coherence drops as functional distance between the team members increases. It is also noted that overall coherence was rather low compared to Figure 14 and Figure 15. This might be due to the lack of participation from production prototyping department and the exclusion of the product stylist. In addition, the coherence between the engineering designer and the product marketer was fairly alike with that between the engineering designer and the product planner. This might be because of the high semantic coherence between the product marketer and the product planner.

5.1.3.4 Semantic Coherence between Production Engineer and Other Team Members

Figure 17 Semantic Coherence between Production Engineer and Other Team Members
(Department index: 1- product marketing, 2-product planning, 3-styling, 4-engineering design, 5-product prototyping, 6-product testing, 7-production)

Figure 17 demonstrates the semantic coherence between the production engineer and the other team members. It was observed that all the coherence scores are rather low, none of which is above 0.5. This may be due to the fact that there were no participants from functionally similar departments, such as product prototyping and product testing department in the design task. Additionally, the semantic coherence between the production engineer and the product marketer was slightly higher than that between the production engineer and the product planner. It was the only point which seemed to violate the pattern expected. However, the semantic coherence between the production engineer and the engineering designer who were three departments away was 0.42, which is still higher than the coherence scores between him and his other two team mates - the product planner and the product marketer, who were five and six departments away, respectively.

In conclusion, the above results confirmed the expected pattern that the semantic coherence decreases as the functional distance between the team members increases. Team member used more coherent semantics when the functional distance between them was smaller. Analyzing the verbal communication of the design team using LSA can capture the semantics of different members in the design team.

5.2 Experimental Study Two: Results and Discussion

5.2.1 Semantic Coherence in Design Teams

5.2.1.1 Semantic Coherence in Design Team One

Figure 18 illustrates the semantic coherence to group centroid of team one. The semantic coherence to group centroid of the four team members was fairly close at the beginning but diverged at the end. The highest semantic coherence to group centroid was 0.6 achieved by speaker B, while the lowest was below 0.4 achieved by speaker D. The running semantic coherence of the groups was not dominated by any of the team members. Hence, the language tracking of the team one was considered rather bad.

Figure 18 Semantic Coherence to Group Centroid of Team One

Table 7 summarizes the semantic coherence between team members of team one. We can see that none of the coherence was above 0.15. Half of the coherence scores were negative. This indicates that the team was unable to reconcile viewpoints. Their conversation was incoherent.

Table 7 Semantic Coherence between Team Members of Team One

	Speaker A	Speaker B	Speaker C	Speaker D
Speaker A	1	-0.046	0.1437	-0.122
Speaker B		1	0.134	-0.289
Speaker C			1	0.148
Speaker D				1

5.2.1.2 Semantic Coherence in Design Team Two

Figure 19. The semantic coherence to group centroid of team member A, C and D were fairly close and ended at around 0.7. The running semantic coherence of the group was totally dominated by the three team members. Speaker B in this team was lagged behind and the upper limit of his coherence was only 0.4. The language tracking of the team was considered rather good since the dominant team members' semantics were tracked closely and the final coherence was fairly high.

Figure 19 Semantic Coherence to Group Centroid of Team Two

Table 8 shows the semantic coherence between any two team members. The semantic coherence between the three dominant team members, A, C and D are relatively high. On the contrary, the semantic coherence between speaker B and the other three are fairly low, even below zero. This indicates that speaker B was not “on the same page” with the other team members.

Table 8 Semantic Coherence between Team Members of Team Two

	Speaker A	Speaker B	Speaker C	Speaker D
Speaker A	1	0.200	0.427	0.219
Speaker B		1	0.036	-0.099
Speaker C			1	0.377
Speaker D				1

5.2.1.3 Semantic Coherence in Design Team Three

Figure 20 shows the running semantic coherence to group centroid of team three. We can see that the semantic coherences to group centroid of team member B and D were closely spaced and rapidly converged towards 1. Speaker C did not strongly follow the group centroid and his semantic coherence to group centroid ended around 0.5. It's worthwhile to attend closely the semantic coherence to group centroid of speaker A and the running semantic coherence of the group. Speaker A's semantic coherence to group centroid was negative for nearly half of the conversation and then began to increase and finally exceeded 0.4. Though his semantic coherence was negative during the initial stage, it was closely spaced with the group's running semantic coherence. This may indicate that speaker A dominated the discussion at the initial stage of the design task and the dominance was taken over by speaker B and D. Moreover, the team experienced some turnings during the whole process, and the group's running semantic coherence showed a sharp change as well. In conclusion, the results showed that the language and knowledge tracking of the team were not perfect.

Figure 20 Semantic Coherence to Group Centroid of Team Three

Table 9 illustrates the semantic coherence between team members. We can see that their coherences are moderately high, all above 0.4.

Table 9 Semantic Coherence between Team Members of Team Three

	Speaker A	Speaker B	Speaker C	Speaker D
Speaker A	1	0.497	0.424	0.542
Speaker B		1	0.515	0.675
Speaker C			1	0.564
Speaker D				1

5.2.2 Experts' Evaluation Results

The results of design process evaluation and design outcome evaluation are summarized in Table 10 and Table 11 respectively.

Table 10 Experts' Evaluation of Design Process

	Team 1	Team 2	Team 3
Goal Clarity	6	6	6
Participation	5	5	6
Decision-Making	5	5	6
Communication	4	6	5.5
Information Sharing	4	5	6
Collaboration	4	5	6
Feedback	4	4	5.5
Conflict	5	5	5
Mutual Support	3	5	6
Productivity	5	4	6
Continuous Improvement	5	5	5
Total	50	55	63

Table 11 Experts' Evaluation of Design Outcome

	Team 1	Team 2	Team 3
Conceptual Design			
Marketability	4.67	4.00	5.33
Profitability	4.00	3.67	3.67
Advancement	4.67	4.00	5.00
Creativity	4.33	4.67	5.67
System-level Design			
Structure of product sub-systems	5.33	4.33	5.33
Functional parameters of product sub-systems	6.00	5.33	5.67
Preliminary assembly blue print	5.00	4.67	6.00
Detail Design			
Detail design of product parts	5.33	4.67	5.33
Procurement	4.33	5.00	6.00
Material and processing technology	5.33	4.67	5.67
Final assembly blue print	5.00	5.33	5.33
Total	54.00	50.33	59

From the experts' evaluation, Team three scored the highest in both design process and design outcome. Team two followed a fairly good design process with 55 points in total, but their outcome was regarded as the worst among the three. On the other hand, Team one scored the lowest in design process evaluation, with only 50 points in total, whereas their design product outperformed team two.

5.2.3 Comparison between Team Semantic Coherence and Experts' Evaluation

Table 12 summarizes the qualitative analyses based on their semantic coherence as well as experts' evaluation of design process and design outcome of the three teams.

Table 12 Summary of Semantic Coherence Analysis and Expert's Evaluation

	Semantic coherence to group centroid	Semantic coherence between team members	Design Process	Design Outcome
Team 1	Rather bad. The semantic coherence to group centroid of the four team members diverged at the end, though they are spaced closely in general.	None of the coherence was above 0.15. Half of the coherence scores were negative.	50.0	54.0
Team 2	Rather good. The semantics of three team converged closely (0.7) at the end. The semantic coherence of the fourth member was sparse.	The semantic coherence between the three dominate team members were relatively high, all above 0.2. The coherence between the fourth member and the others was fairly low, even below zero.	55.0	50.3

Team 3	Not perfect. Two team members' semantics converged (>0.7) at the end. The semantic coherence of the other two was sparse.	The semantic coherence between any of the four members were relatively high, all above 0.4	63.0	59.0
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For team one, the results of the two semantic coherence metrics revealed that the team was not successful in establishing a coherent discussion and the shared understanding between team members was low. The results were consistent with the experts' evaluation of the team's design process. According to the experts' assessment, team one performed fairly bad in mutual support of each other. The members of team one did not help one another when individuals needed assistance. Besides, the quality of their communication, information exchange, collaboration, and feedback were not high, scoring 4 points in the 7-point Likert scale. Although accompanied by a poor design process, the design outcome of team one turned out to be acceptable. The design outperformed team two and even scored the highest in 4 out of the 11 criterion, including profitability, structure of product sub-systems, functional parameters of product sub-systems and detail design of product parts.

The semantic coherence to group centroid indicated that the language tracking of team two was rather good. With a measure of 0.7, the three team members converged to a high coherence score. However, the analysis of semantic coherence between team members showed that team member B had low level of coherence with the other members, and even a negative coherence with team member D. This indicated that person B was constantly not "on the same page" with the team. With a close

examination of the transcripts of team two, we found that among the 1919 content-bearing utterances, person B only contributed 392 utterances, the least among all the team members. Besides the lack of participation in terms of number of utterances, person B intervened with the process of the rest of team obviously. Let me illustrate this with an example from their discussion in system-level design stage. The team used 121 utterances in total to decide the length between the front wheel and the back wheel. Out of them, person B uttered 12 times. While the rest of the team was actively calculating that parameter, person B suggested that they did not need the accurate number of the length.

B: 算了我们也不要那么精确就是换算一下.

B: It doesn't matter, we don't have to be that accurate, just convert it.

This suggestion was ignored by the others. The rest of the team proceeded to compute the length of the parameter.

This destructive influence seemed to strongly affect the performance of team two, resulting in a relatively ordinary design process quality and poor design quality. From the experts' evaluation, team two secured an average point 5 for the design process. However, it scored the lowest in 10 out of the 11 criteria and did the worst in the three groups in term of design outcome.

For team three, the results from semantic coherence to group centroid were not perfect. Two team members' semantics converged to a high level at the end, while the

semantic coherence levels of the other two were low. Despite this imperfection, the analysis of semantic coherence between team members showed high levels of coherence. This indicated that each team member was actively involved in the design task and had a moderately high level of shared understanding with the other members. In this premise, the sparse semantic coherence at the initial stage might signify an exploration of ideas during the conceptual design. After the team finalized their design concept, their semantic coherence converged rapidly. Comparing the analysis based on LSA with the expert evaluation, there is great consistency between the two. Team three outperformed the other two teams in terms of both design quality and design outcome. Moreover, the creativity score of design team three was at least 20% higher than that of the other two teams. This confirmed our previous speculation that this team experienced brainstorming of design ideas at the beginning of the task.

In conclusion, we can see that the two semantic coherence metrics complement each other. By combining the two, we developed a better way of characterizing the semantic coherence of the team. Moreover, the results also showed that the semantic coherence of the team was more correlated to design process than design outcome. In our study, the level of semantic coherence of each team was consistent with the design process quality, but did not fully explain the variation in design outcome quality.

Chapter 6: Conclusion and Future Work

This concluding chapter summarizes the findings of this study in Section 6.1 and the contributions of the thesis work in Section 6.2. The limitations and possible improvements of this research are also discussed, along with avenues for future research, in Sections 6.3 and 6.4, respectively.

6.1 Conclusion

As the scope and complexity of modern design task demands exceed the capability of individuals to perform, teams are emerging to shoulder the growing requirements. The benefit of a design team lies in its ability of integrating the variety of designers' experience, perspectives and detailed knowledge. The dynamic nature of design team results in studies on social behavior and cognition, psychometrics, sociometry, computational linguistic techniques and so forth. As one of the computational linguistic techniques, Latent Semantic Analysis is able to extract the latent meaning in design communication and rapidly analyze a large number of design documents. This characteristic offers the potential to develop design aid which can enhance the communication of design teams. Previous research aimed to find the relationship between semantic coherence of design teams' communication and design process quality as well as design outcome quality (Dong, 2004, 2005; Dong et al., 2004; Hill et al., 2002). Some good results have been reported. However, review of theories on team performance and design team suggests the necessity to decouple the design process and design outcome. Analyzing design process and design outcome separately will better justify the use of latent semantic analysis in evaluating design team interaction.

Different quantitative metrics were proposed to analyze coherence in various contexts. The "semantic coherence to group centroid" metric (Dong, 2005) measures the process of how a team member acquires the common semantics of the team. We propose a measure of "semantic coherence between team members" to measure the

similarity and semantic coherence between team members. The two metrics complement each other to provide better prediction power on team performance. Results from the two metrics showed that design teams' verbal communication coherence is more correlated to design process than design outcome.

Dorst (2008) considered design as a “complex creative human endeavour”. Researchers strive to understand how to make such an endeavour successful. Research has been conducted to address this question from different perspectives, including studies of the design process, composition of design teams, design creativity, content-oriented design, use of CAD tools and so forth. The author believes that for such a complex system, it is difficult to draw any definite causal relationships determining what will result in successful outcome. However, design research in the past four decades has proven that a good design process is important for design teams to produce successful products. In the context of product design, successful product outcomes demonstrate that the organization's “commercial” objectives have been met. On the other hand, a focus on how the process was accomplished is important for diagnosing performance problems that may inhibit positive product outcomes. To ensure consistently effective performance, it is necessary to measure both design process and design outcome.

6.2 Contributions

The main contributions can be briefly described as follow:

- Examined the credibility of using LSA to capture the semantics of different design team members during their conversation.
- Proposed a new metric which computes the semantic coherence between team members. The new metric and existing “semantic coherence to group centroid” metric complement each other and offer better modeling of design team verbal communication.
- Explored the relationship between semantic coherence and design process quality, between semantic coherence and design outcome quality separately. Confirmed the speculation that design teams’ verbal communication coherence is more correlated to design process than design outcome.

6.3 Limitations

There are several limitations of this research and the results have to be viewed in the light of these limitations.

The sample size is limited. It is difficult to get access to experienced designers. Only one design team was examined in study one. However, the multi-disciplinary nature of the team provided four different sets of data. In study two, three design teams were recruited and analyzed. The results based on semantic coherence and experts’ evaluation was consistent with our postulation. However, the limited sample size was not able to justify the statistical power.

The second limitation is due to the methodology of thinking aloud. To be able to record the design process, the designers were asked to think aloud. Though considered

to be easy to learn and not very distracting, thinking aloud might have changed the designer's way of working.

Although a laboratory environment is an advantage for comparative research, it restricts the design process and thus the variables in a study. The designers had to work in a room where every action and utterance were observed and recorded. They were not surrounded by their own 'tools' and had to work with the information provided. However, this is expected to be the same for all teams in this study. This study simulated well the real design environment and all the designers were comfortable in their work.

6.4 Future Work

This thesis raises several opportunities for further research.

We postulate that there exists an inverted U relationship between the metric and design team performance, where extremely high levels of semantic coherence between team members indicates the two members' understandings of the problem are very similar, resulting in "group think" phenomena, while a low level or even negative level of semantic coherence between team members signifies the two members are not "on the same page" at all. However, due to the limited sample size, this relationship was not fully explored in this research. Therefore, further studies can be carried out to model this relationship quantitatively.

The interaction between the two metrics, namely semantic coherence to group centroid and semantic coherence between team members was limited to a qualitative analysis in our study. This provides opportunities to further examine the interaction, resulting in rule-based principles. These rule-based principles offer monitoring aid to design teams.

The number of scores for semantic coherence between team members equals to $c(n,2)$, where n is the number of team members in a design team. As the number of team members increases, the number of combinations increases more rapidly. Therefore, it may be useful to have some summary measures (e.g. mean, variance, range), especially when number of team members involved is large. These summary measures can provide us a holistic view and a quick summary on design teams' communication status.

LSA as one technique in computational linguistics is able to quantify the semantic coherence in a team. It offers a bird eye's view of whether the team is "on the same page", but it is unable to provide detailed information on what the design team has discussed. On the contrary, another computational linguistic technique - Lexcial Chain Analysis (LCA) has the ability of extract the thesaural structure of a text (Morris & Hirst, 1991). Thus LCA is able to understand the content of a design team's discussion. A combination of the two techniques is expected to provide better monitoring of design teams' communication and enhance their design process and outcomes.

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Appendix A: Source Code for Constructing Word-by-document Matrix

```
Imports System.IO
Imports System.Data.OleDb

Module Module1

    Sub Main()

        'create datatable
        Dim newdataset As DataSet = New DataSet("New Dataset")
        Dim newdatatable As DataTable = New DataTable("New datatable")

        Dim uttercol As DataColumn = New DataColumn("col")
        uttercol.AllowDBNull = True
        newdatatable.Columns.Add(uttercol)

        ' read each line of the txt file
        Dim sr As StreamReader = New StreamReader("C:\Documents and
Settings\CHFE\Desktop\sample_cla.txt", System.Text.Encoding.Default)

        Dim line As String
        line = sr.ReadLine
        Dim rowindex As Integer = 1

        Dim prewriter As StreamWriter = File.CreateText("C:\Documents and
Settings\CHFE\Desktop\pre-essentialwords.txt")

        Do
            ' prewriter.Write(rowindex & " ")
            Dim newrow As DataRow = newdatatable.NewRow()
            newrow.Item(0) = rowindex
            rowindex = rowindex + 1
            For i As Integer = 1 To newdatatable.Columns.Count - 1
                newrow.Item(i) = 0
            Next

            Dim sa As String() = Nothing
            sa = line.Split(" ") ' split according to space
            Dim linelength As Integer
            linelength = sa.GetLength(0)

            Dim light As Boolean = True
            Dim s As String
            For Each s In sa

                If s <> "" Then

                    ' for english data, include nouns NN,NNP,NNPS, NNS; verbs
                    VB, VBD,VBG,VCN,VBP,VBZ; adj JJ, JJR, JJS; adv RB, RBR, RBS
                    'If s.EndsWith("/NN") Or s.EndsWith("/NNS") Or
                    s.EndsWith("/NNP") Or s.EndsWith("/NNPS") Or s.EndsWith("/JJ") Or
                    s.EndsWith("/JJR") Or s.EndsWith("/JJRS") Or s.EndsWith("/VB") Or
                    s.EndsWith("/VBD") Or s.EndsWith("/VBG") Or s.EndsWith("/VCN") Or
```

```

s.EndsWith("/VBP") Or s.EndsWith("/VBZ") Or s.EndsWith("/RB") Or
s.EndsWith("/RBR") Or s.EndsWith("/RBS") Then
    '-----
    ' for chinese data, include nouns /n, verbs
/v,adjectives/a, adverbs/d
    If s.EndsWith("/n") Or s.EndsWith("/v") Or
s.EndsWith("/a") Or s.EndsWith("/d") Or s.EndsWith("/q") Or s.EndsWith("/f")
Or s.EndsWith("/g") Or s.EndsWith("/b") Or s.EndsWith("/s") Or
s.EndsWith("/j") Or s.EndsWith("/l") Then
        If s.StartsWith("是/v") = False And s.StartsWith("是
/a") = False And s.StartsWith("不/a") = False And s.StartsWith("不/d") =
False And s.StartsWith("的/b") = False And s.StartsWith("不要/d") = False And
s.StartsWith("不能/v") = False And s.StartsWith("能/v") = False Then

            ' If s.StartsWith("be/V") = False And
s.StartsWith("n't/R") = False And s.StartsWith("is/V") = False And
s.StartsWith("'s/V") = False And s.StartsWith("was/V") = False And
s.StartsWith("are/V") = False And s.StartsWith("'re/V") = False And
s.StartsWith("am/V") = False And s.StartsWith("'m/V") = False And
s.StartsWith("were/V") = False And s.StartsWith("do/V") = False And
s.StartsWith("does/V") = False And s.StartsWith("did/V") = False And
s.StartsWith("done/V") = False And s.StartsWith("didn/V") = False And
s.StartsWith("will/") = False And s.StartsWith("'ll/") = False And
s.StartsWith("'ve/V") = False And s.StartsWith("have/V") = False And
s.StartsWith("yes/") = False And s.StartsWith("no/") = False And
s.StartsWith("not/") = False Then
                Console.WriteLine(s)
                light = False

                prewriter.Write(s & " ")

            End If
        End If
    End If

Next

If light = True Then
    prewriter.Write("no essential words in the sentence")
End If
' rowindex = rowindex + 1
line = sr.ReadLine
prewriter.WriteLine()

Loop Until line Is Nothing

prewriter.Close()

End Sub

End Module

Imports System.IO
Imports System.Data.OleDb

Module Module1

```

```

Sub Main()

    'create datatable
    Dim newdataset As DataSet = New DataSet("New Dataset")
    Dim newdatatable As DataTable = New DataTable("New datatable")

    Dim uttercol As DataColumn = New DataColumn("col")
    uttercol.AllowDBNull = True
    newdatatable.Columns.Add(uttercol)

    ' read each line of the txt file
    Dim sr As StreamReader = New StreamReader("C:\Documents and
Settings\CHFE\Desktop\pre-essentialwords.txt", System.Text.Encoding.Default)

    Dim line As String
    line = sr.ReadLine
    Dim rowindex As Integer = 1

    Do

        Dim newrow As DataRow = newdatatable.NewRow()
        newrow.Item(0) = rowindex
        rowindex = rowindex + 1
        For i As Integer = 1 To newdatatable.Columns.Count - 1
            newrow.Item(i) = 0
        Next

        Dim sa As String() = Nothing
        sa = line.Split(" ") ' split according to space
        Dim linelength As Integer
        linelength = sa.GetLength(0)

        Dim s As String
        For Each s In sa

            If s <> "" Then

                Dim firstcha As Char
                firstcha = s.Chars(0)

                ' for english data, include nouns NN,NNP,NNPS, NNS; verbs
                VB, VBD,VBG,VCN,VBP,VBZ; adj JJ, JJR, JJS; adv RB, RBR, RBS numerical CD
                ' If s.EndsWith("NN") Or s.EndsWith("NNS") Or
                s.EndsWith("NNP") Or s.EndsWith("NNPS") Or s.EndsWith("JJ") Or
                s.EndsWith("JJR") Or s.EndsWith("JJS") Or s.EndsWith("VB") Or
                s.EndsWith("VBD") Or s.EndsWith("VBG") Or s.EndsWith("VCN") Or
                s.EndsWith("VBP") Or s.EndsWith("VBZ") Or s.EndsWith("RB") Or
                s.EndsWith("RBR") Or s.EndsWith("RBS") Or s.EndsWith("CD") Then

                    ' -----
                    ' for chinese data, exclude c-conjunction,e-exclamation
                    g-yusu h-qianjie i-idiom k-houjie o-nisheng p-prep u-zhuci w-biaodian x-
                    feiyusu y-yuqici z-zhuangtaici
                End If
            End For
        Next
    Do

```

```

        'If s.EndsWith("c") = False And s.EndsWith("e") = False
And s.EndsWith("g") = False And s.EndsWith("h") = False And s.EndsWith("i") =
False And s.EndsWith("k") = False And s.EndsWith("o") = False And
s.EndsWith("p") = False And s.EndsWith("u") = False And s.EndsWith("w") =
False And s.EndsWith("x") = False And s.EndsWith("y") = False And
s.EndsWith("z") = False Then

-----
'-----

'    If firstcha.IsUpper(s.Chars(0)) = False And
firstcha.IsPunctuation(s.Chars(0)) = False And s.EndsWith("n") Or
s.EndsWith("a") Or s.EndsWith("v") Or s.EndsWith("d") Or s.EndsWith("b") Or
s.EndsWith("t") Or s.EndsWith("m") Or s.EndsWith("q") Or s.EndsWith("r") Then

        Dim y As Integer
        'Dim dcc As DataColumnCollection
        Dim z As Integer
        z = newdatatable.Columns.Count
        Dim indicator As Boolean = False
        For y = 1 To z
            If s = newdatatable.Columns(y - 1).ColumnName Then
                indicator = True
                Exit For
            End If
        Next

        If indicator = True Then
            'newdatatable.Rows(rowindex)(y - 1) =
newdatatable.Rows(rowindex)(y - 1) + 1
            newrow.Item(y - 1) = newrow.Item(y - 1) + 1
            'newdatatable.Columns(y-1).
        Else
            Dim coll As Int16 = newdatatable.Columns.Count
            Dim newdatacol As DataColumn = New DataColumn(s)
            newdatacol.DataType =
System.Type.GetType("System.Int32")

            newdatatable.Columns.Add(newdatacol)
            newrow.Item(z) = 1
        End If

    End If
' End If
Next
newdatatable.Rows.Add(newrow)

' rowindex = rowindex + 1
line = sr.ReadLine
Loop Until line Is Nothing

For i As Integer = 0 To newdatatable.Rows.Count - 1
    For j As Integer = 0 To newdatatable.Columns.Count - 1
        Dim te As Object

        te = newdatatable.Rows(i).Item(j).toString
        ' Console.WriteLine(newdatatable.Rows(i).Item(j).ToString)
        If newdatatable.Rows(i).Item(j).ToString = "" Then

```



```

        newdatatable.Rows(i).Item(j) = 0
    '
    Console.WriteLine(newdatatable.Rows(i).Item(j).ToString)
    End If
Next
Next

Dim mywriter As StreamWriter = File.CreateText("C:\Documents and
Settings\CHFE\Desktop\matrix_withoututterance.txt")
Dim wordwriter As StreamWriter = File.CreateText("C:\Documents and
Settings\CHFE\Desktop\wordinput_withoututterance.txt")

'-----
' Caution: make sure you produce two matrix file. one is with the
utterance index (the following j=0), the other is without the utterance index
(the following j=1).
' the latter one is for the next matlab analysis, but the former one
maybe useful in the case that there is one utterance whose cells
'contains only zeros in the entire column. in that case, that
utterance should be eliminated
'-----
For j As Integer = 1 To newdatatable.Columns.Count - 1

    Dim colsum As Integer = 0
    For i As Integer = 0 To newdatatable.Rows.Count - 1
        Console.WriteLine("{0}", newdatatable.Columns(j).ColumnName)
        colsum = colsum + newdatatable.Rows(i).Item(j)
    Next

    Console.WriteLine(newdatatable.Columns.Count)

    If colsum >= 2 Then
        Console.WriteLine("{0}", newdatatable.Columns(j).ColumnName)
        Console.WriteLine(newdatatable.Columns(j).ColumnName.ToString
& "" & Chr(9) & "")
        wordwriter.Write(j & Chr(9) &
newdatatable.Columns(j).ColumnName.ToString & Chr(13) + Chr(10))

        Dim myarray(newdatatable.Rows.Count) As Integer
        myarray(0) = j
        For k As Integer = 0 To newdatatable.Rows.Count - 1
            myarray(k + 1) = newdatatable.Rows(k).Item(j)
        Next
        writearray(myarray, mywriter)
    End If
Next
mywriter.Close()

wordwriter.Close()

End Sub

Sub writearray(ByVal myarray As Array, ByVal mywriter As StreamWriter)

    For index As Integer = 1 To myarray.Length - 1
        Console.Write(myarray(index) & "" & Chr(9) & "")
        mywriter.Write("{0}", myarray(index))
    Next
End Sub

```

```
        ' mywriter.WriteLine("{0}", index)
        mywriter.Write(" " & Chr(9) & " ")

    Next

    mywriter.WriteLine("")

End Sub

End Module
```

Appendix B: Source Code for Log-entropy Matrix

```
function le = logentropy(x)
% LOGENTROPY Compute the log-entropy weighted matrix
% X is a word by document matrix of raw frequency counts.

nwords = size(x,1);
ndocs = size(x,2);

% normalized word count
for i=1:nwords,
    for j=1:ndocs,
        p(i,j)=x(i,j)/sum(x(i,:));
    end
end

% word entropy
e=zeros(1,nwords);
for i=1:nwords,
    for j=1:ndocs,
        if (p(i,j) > 0),
            e(i) = e(i) - p(i,j)*log2(p(i,j))/log2(ndocs);
        end
    end
end

for i=1:nwords,
    for j=1:ndocs,
        le(i,j) = log2(1+x(i,j))*(1-e(i));
    end
end
```

Appendix C: Task Design for Experimental Study One

Instruction

The study team thank you for your participation. We are interested in the ways that the concurrent engineering team work on design projects. This experiment is being videotaped for later analysis by a number of researchers. I am going to ask you to undertake a short design project. Let me assure you that no commercial advantage will be taken of any design work or ideas that you produce. All your responses will be treated in strict confidence and the identities of companies, projects and people will be KEPT confidential and proprietary. Your remarks and responses will be presented in a sanitized form through coding and modeling. Any verbatim remarks used in the write-up will also be sanitized to protect your identity. In addition, any data that describes a specific product feature or release will be shown in an unlabeled form to protect proprietary information. We appreciate your time and input.

Because we want to understand what you are thinking during the task, we want you to think aloud continually during the session. This would be as if you are talking to yourself but loud enough for me to hear. The total time available for your design is limited to 2 hours. In a moment I will give you a short written design brief for the project.

Drawing materials-paper, pencils, pens and markers-are available for your use. Please work as you normally would on such a design project as this. Before I give you the design brief, are there any questions about the experiment?

If there are no further questions, we will start the session now. I remind you that the maximum time available to you is 2 hours. I will remind you of the time at 30 minutes and 15 minutes before the end, if you are still working.

Survey on Background Information

Firstly, please take a few moments to fill out some information for classification purposes.

Your Name: _____

Have you ever worked with your today's team members? If yes, how long?

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

How familiar do you know your today's team members? Please rate your response according to the following categories.

1	2	3	4	5	6	7
Extremely Unfamiliar	Very Unfamiliar	Unfamiliar	Neutral	Familiar	Very Familiar	Extremely Familiar

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Design Task

The automotive enterprises are becoming more customer-centric to meet today's challenging market demands. One of the major parts of the car, the car seat, plays an important role in providing a complete user experience.

The main requirement of car seat design is to keep passengers comfortable and safe. Besides the conventional requirement, the emotional intention or the *citarasa* of customers also begin to draw attention from the automotive enterprises.

Nowadays, many automotive enterprises are taking the advancements of car seat design and competing to be considered the most luxurious and to set the standard in ergonomic seat design. For example, one invention, the BackCycler CPM(tm), inflates and deflates to change the lumbar support that the seat provides for the back on a normal interval to stimulate different muscles to do the work of carrying the load in your back. This device has been made to integrate it into Volvo's seats.

As a response to this trend, your company has decided to develop an innovative product and sees this as a good opportunity to profit from the East Asian market. Your team has been engaged to design this future driver seat. Your company wants your team improve your current driver seat design and to propose a "new and exciting" product, addressing the conventional requirement of comfort and safety, as well as the *citarasa* needs of customers and end user.

You are a valued member of this team. You come with very important knowledge, skills and expertise which are unique to your experience. You will contribute to the design of the product according to the expertise that you have. The product your team designed should be accordable with your company's background. Your team needs to list down all of your considerations in design, concentrating on:

- Safety

- Comfort
- Ease of use
- Appealing form
- Demonstrating the technical feasibility of the design
- Ensuring that the product stays within a reasonable price range

Your team is required to finish the design in 2 hours. Please design this product according to the existing design process in your company. This would be like a mini version of the design process which may take a few months or even years. Your team is strongly suggested to make full use of your team members' expertise so that your team can finish all the design of your product.

The output of the design task is suggested to contain:

- The annotated sketch of your product explaining your design
- The product's features and specifications of the geometry, materials and tolerances of all the unique parts in the product.
- A preliminary process flow diagram for the final assembly process
- A list of the standard parts to be purchased from suppliers
- A process plan for each part to be fabricated within the production system
- Any other important information that is important in the design process

HAPPY WORKING!

Appendix D: Task Design for Experimental Study Two

Instruction

The study team thanks you for your participation. We are interested in the ways that designers work on design projects. This experiment is being videotaped for later analysis by a number of researchers. I am going to ask you to undertake a short design project. Let me assure you that no commercial advantage will be taken of any design work or ideas that you produce. All your responses will be treated in strict confidence and the identities of companies, projects and people will be KEPT confidential and proprietary. Your remarks and responses will be presented in a sanitized form through coding and modeling. Any verbatim remarks used in the write-up will also be sanitized to protect your identity. In addition, any data that describes a specific product feature, or release will be shown in an unlabeled form to protect proprietary information. We appreciate your time and input.

Because we want to understand what you are thinking during the task, we want you to think aloud continually during the session. This would be as if you are talking to yourself but loud enough for me to hear. The total time available for your design is limited to 6 hours, divided by 3 2-hour sessions. In a moment I will give you a short written design brief for the project.

Drawing materials-paper, pencils, pens and markers-are available for your use. Please work as you normally would on such a design project as this. Before I give you the design brief, are there any questions about the experiment?

If there are no further questions, we will start the session now. I remind you that the maximum time available to you in this session is two hours. I will remind you of the time at 30 minutes and 15 minutes before the end of the session, if you are still working.

Happy working!

Survey on Background Information

Firstly, please take a few moments to fill out some information for classification purposes.

Your Name: _____ Sex: _____ Age: _____

Education : ☐ Bachelor ☐ Master ☐ PhD ☐ Other Major: _____

Company: _____ Job Title: _____

How long in average does your typical project last? _____

How many years have you worked in a design team? _____

What are main products that you have designed in the past?

Have you ever worked with your today's team members? If yes, how long?

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

How familiar do you know your today's team members? Please rate your response according to the following categories.

1	2	3	4	5	6	7
Extremely Unfamiliar	Very Unfamiliar	Unfamiliar	Neutral	Familiar	Very Familiar	Extremely Familiar

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Can you tell me your E-mail address? _____

Design Task

CHFECycling Inc. is a large Singapore firm that produces innovative cycling devices. They have been very successful over the last ten years and are well known internationally for making some of the best vehicles, such as road bicycle, tandem bicycle, unicycle, Mini Scooter, Electric Scooter, Trike etc. However, in the last one and a half years, this company has suffered some setbacks in the market.

As a response, CHFECycling Inc. has hired a marketing firm to look for new trends and opportunities for the East Asian market. On the basis of this marketing report, CHFECycling Inc. has decided to develop an innovative product for the young adults in East Asian. The device can be any purpose of cycling, such as entertainment, race, working, indoor, or outdoor, but should be lightweight, easy to ride and keep, innovative and aesthetically exciting.

This idea is particularly interesting for CHFECycling Inc., because the director, Mr Ng, sees this as a good opportunity to profit from the East Asian marketing. Your team has been engaged by CHFECycling Inc. to design this future device. Many different types of products already exist in the market. CHFECycling wants your team to propose a “new, original and exciting” product that is not yet available in the market.

You are a valued member of this team. You come with very important knowledge, skills and expertise which are unique to your experience. You will contribute to the

design of the product according to the expertise that you have. The product your team designed should be accordable with your company's background. Your team needs to

list down all of your considerations in design, concentrating on:

Safety

Ease of use

Appealing form

Demonstrating the technical feasibility of the design

Ensuring that the product stays within a reasonable price range

Your team is suggested to develop this product according to the following three phases:

Conceptual Design. In this phase, the needs of the target market are identified, alternative product concepts are generated and evaluated, and a single concept is selected for further development and testing. A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the project. The concept development phase is more critical to the whole process, and demands more coordination among functions than any other.

System-level Design. This phase defines the product architecture, and divides the product into subsystems and components. The final assembly scheme for the production system is usually defined during this phase as well. The output of this phase is usually a geometric “layout” of the product, a functional specification of each

of the product's subsystems, and a preliminary process flow diagram for the final assembly process.

Detail Design. Detail Design includes the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is the control documentation for the product-the drawing files describing the geometry of each part and its production tooling, the specifications of the purchased parts, and the process plans for the fabrication and assembly of the product.

You may adjust the design phases according to the expertise of your team, but your team is required to finish the design in three 2-hour sessions. Your team is strongly suggested to make full use of your team members' expertise so that your team can finish all the design of your product. The CEO of CHFECycling Inc. and the directors of the company will evaluate your design based on all the description of your design.

Task 1: Conceptual Design

In this phase, you are suggested to identify the needs of the target market, generate alternative product concepts and evaluate them, and a single concept is selected for further design. Your team is encouraged to generate several ideas and finally choose one promising idea for conceptualization.

Your team also needs to describe your product in a piece of paper (A3 size). Your description is suggested to contain:

The name of your product

The annotated sketch of your product explaining your concept design

The product's features

Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

HAPPY WORKING!!

Task 2: System-level Design

In this phase, basing on the conceptual design in last session, your team needs to define the product architecture, and divide the product into subsystems and components. The final assembly scheme for the production system is usually defined during this phase as well. The output of this phase is usually a geometric “layout” of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.

Your team also needs to describe your product in this phase in a piece of paper (A3 size). Your description is suggested to contain:

The annotated sketch of your product explaining your design

The product's features and specifications

Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

HAPPY WORKING!!

Task 3: Detail Design

In this phase, based on your design in the past two sessions, your design needs to include the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is the control documentation for the product-the drawing files describing the geometry of each part and its production tooling, the specifications of the purchased parts, and the process plans for the fabrication and assembly of the product.

Due to time limitation, your team can choose several key parts of your product according to your team's expertise, and design them in detail. Your team also needs to describe your detail design in a piece of paper (A3 size). Your description is suggested to contain:

The annotated sketch of your whole product explaining your design

Specifications and detail information of your key parts design

Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

HAPPY WORKING!!

Appendix E: Evaluation Criteria for Design Process

Goal Clarity

There is a lack of clearly understood goals

Goals are clear and agreed upon

Participation

Participation is unequal and some people do more work than others

Participation is equitable and everyone does their fair share of work

Decision-Making

There is little opportunity to participate in decisions or provide input

There is a lot of opportunity to participate in decisions and provide input

Communication

Communication is poor and team members are not open and honest with one another

Team members are open, honest, and direct in their communication

Information Sharing

Information is shared selectively with a few team members

Information is shared widely and everyone is kept up-to-date on important issues.

Collaboration

There is little collaboration and not much cooperation between team members

Team members work well together and coordinate their work

Feedback

Team members do not give feedback to one another and do not feel free to share perceptions openly

Team members give feedback to one another and share their perceptions in a way that is helpful and constructive

Conflict

Conflict is avoided, denied, or suppressed

Conflict is accepted as part of team development and addressed effectively

Mutual Support

Team members do not help one another when individuals need assistance

Team members readily help one another

Productivity

The team does not produce results and works ineffectively

The team produces results and works effectively

Continuous Improvement

The team does not seek ways to improve its results, process, and relationships.

The team seeks to continuously improve its results, processes, and relationships.

Appendix F: Evaluation Criteria for Design Outcome

1	2	3	4	5	6	7
非常不同意	不同意	稍微不同意	中立	稍微同意	同意	非常同意
Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

	设计小组 1 Design team 1
总体评价 Overall Evaluation	
第一阶段 Conceptual Design	
1.市场性：产品概念满足了目标市场的需求 Marketability: product concept meets the requirements of the target market	
2.效益性：产品概念具有经济效益 Profitability: product concept is going to generate profit	
3.先进性：产品概念比市场上现有产品更为合理或有独到之处 Advancement: product concept is more advanced/reasonable than existing products in the market	
4.创造性：产品概念与市场上现有产品相比，具有新的特征和创新 Creativity: product concept is more creative than existing products in the market	
第二阶段 System-level Design	
5.产品的子系统结构是合理的 Structure of product sub-systems: design of product sub-systems structure is reasonable	
6.产品的功能性参数是定义充分并且合理的 Functional parameters of product sub-systems: design product sub-systems functional parameters is adequate and reasonable	
7.产品预备性的装配方案是充分并且合理的 Preliminary assembly blue print: design of preliminary assembly process is adequate and reasonable	
第三阶段 Detail Design	
8. 对产品特定部件的设计是充分并且合理的 Detail design of product parts: product parts detail design is adequate	

and reasonable	
9. 产品的采购方案是充分并且合理的 Procurement: product procurement plan is adequate and reasonable	
10. 对产品主要部件材料和加工工艺的选择是合理的 Material and processing technology: selection of product material and processing technology are reasonable	
11. 参品装配方案是充分并且合理的 Final assembly blue print: design of final assembly process is adequate and reasonable	