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LATENT SEMANTIC ANALYSIS MEASURES PARTICIPANT AFFILIATION AND TEAM PROCESS QUALITY

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ABSTRACT
This paper presents a new method to measure stakeholder affiliation and team process quality based on latent semantic analysis (LSA). It makes important clarifications to published measurements of semantic coherence as an indicator of shared knowledge in design. A new method is proposed to measure semantic coherence between members during a group setting. It complements the existing method by measuring the communication similarity between stakeholders. The research is based on a study of experienced product designers in China. Homogeneous teams of experienced product designers with similar backgrounds are formed to study the relation between semantic coherence and process and product outcome. The study finds that teams with high levels of semantic coherence between each participant *and* between each participant and the group are likely to have high quality processes. The team process, however, is not strongly correlated to a high quality design outcome.

Keywords: collaborative design, new product development, knowledge integration

1. INTRODUCTION
Today, teams of people design. The advantage of design teams is 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 consensus through activities such as information exchange, compromise and negotiation [1].
Studies of collaborative design teams are based on methods including psychometrics, sociometry, and computational linguistic analysis. Despite different disciplinary roots, researchers in these areas are all inspired by one question - why do some design teams succeed whereas others fail? To answer this question, design researchers have been investigating the thinking behavior of participants in design teams. Several issues have been investigated, including the strategies for reaching shared understanding [2] and the patterns of basic cognitive processes in design teams [2, 3]. Researchers specializing in psychometrics explored how the composition of design teams from individuals who are placed on teams affects the outcomes [4]. These "actor level" behaviors combined with organizational and project level behaviors ultimately influence the achievement of shared understanding in design and the design process [5].
With the advent of high-speed computation, computational text analysis becomes a new method for studying design teams. Mabogunje and Leifer [6] explored the relationship between design creativity and the number of noun phrases generated in the conceptual design stage and found positive correlation between them. More recently, Dong and his colleagues used Latent Semantic Analysis (LSA) to assess the performance of design teams [7-10]. 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 [11]. Hill, Dong, and Agogino [9] explored the relationship between design document semantic coherence, team cohesiveness, shared understanding, and design process and design (product) outcome quality. 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 [9]. This can be considered a framework for studying team communication based on LSA.

Based on this framework, Dong, Hill, and Agogino [10] studied the relation between coherent design documentation and successful engineering design outcomes. To quantify the semantic coherence of design documentation, they proposed two textual coherence metrics based on LSA and found a positive correlation between design document semantic coherence and the design outcomes. However, the two metrics used to characterize semantic coherence of design documents were not suitable for analysis of conversations due to the unstructured nature of conversations. Hence, Dong [7] suggested another method to assess semantic coherence in design conversations by computing the average semantic coherence between utterances which were distally close, the intuition being that utterances “nearby” should be more semantically coherent than utterances “far apart”. The underlying idea was that there should be an orderly mapping between semantic coherence and distance between utterances. In a later study, Dong [8] introduced the “knowledge convergence” method to compute how an individual’s language becomes similar to the group’s overall language. He stated that the method indicates an acquisition of common semantics as well as an acquisition of a socially held representation of a design artifact. There has not yet been a study that quantified the level of coherence of the conversation between participants and to correlate that coherence to successful outcomes.

The framework proposed by Hill, Dong, and Agogino [9] regarded design process quality and design outcome quality as a union. In the corresponding study, experts rated each team and produced one rating to quantify the team quality (as a union of process and product outcome). However, studies of teamwork suggest the necessity to measure processes and outcomes separately. Paris, Salas and Cannon-Bowers [12] stated that process and outcome measures complement one another, and, together, they provide a complete picture of team performance. 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. Because flawed team processes can occasionally result in successful product outcomes, it is necessary to measure both if one is to ensure consistently effective performance. Furthermore, the literature on design creativity identifies the importance and significance of creativity for successful design outcomes [13-15]. Due to the emotional nature of creativity, it rarely comes with standard processes. 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. Moreover, we speculate that the coherence of communication in design teams is more correlated to design process than design outcome. In addition, we propose to expand on the “concept centroid” idea proposed in [8] from the whole team to each team member. This idea is inspired by the notion of groupthink. Groupthink was defined by Irving Janis [16] 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. To measure this phenomenon, one would need to ascertain the “concept centroid” for each speaker and determine how closely it tracks the “concept centroid” of another speaker. Thus, we have developed a way to more precisely measure the semantic coherence between group members (participant affiliation) during a design conversation. Using this method, we can explore the relation between inter-participant semantic coherence in a conversation and design process and product outcome quality. We believe that this measure can depict how well the participants are working together even if they apparently do not seem to be working closely as a team because they have different roles to play within the group situation. These different roles may manifest as varying semantics, resulting in a false negative of low group semantic coherence. The false negative can be rectified by examining inter-participant affiliation since each participant is (at least) speaking to the other participants, if not to the group as a single entity, and should share semantic coherence with at least one other participant.

There are two objectives in this research:

1. To explore the relationship between semantic coherence and design process quality and design outcome quality separately
2. To propose a new method to measure semantic coherence in a design group’s verbal communication

2. METHODOLOGY

2.1 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 [11]. It has been applied to a wide range of problems for identifying the contextual meanings of words and documents, including information retrieval [17, 18], assessing learning [19, 20], modeling knowledge acquisition [11], identifying shared understanding in design [21], characterizing design team performance [10] and predicting team performance on simulated military mission [22].

The mathematical components of LSA are well documented, and the reader is referred to [8] for a complete review. The standard procedures finclude five steps. The innovation in the research is the method for handling inter-participant communication, the details of which will be discussed in step 5. The latent semantic approach is as follows:

1. ***Capture design team's verbal communication***
2. ***Transcribe and process text***

In this study, a language parser for Chinese [24] is used to segment utterances and assign part-of-speech to each word. Only essential words are extracted for step 3.

3. ***Create a word-by-document matrix and log-entropy matrix***

A word-by-document matrix counts the number of occurrences of each essential word in each utterance. The word-by-document matrix may optionally be transformed to log-entropy form, which expresses both a word's importance in the particular passage and the amount of information the word carries in the passage [25].

4. ***Apply singular value decomposition and construct k-reduced matrix***

MATLAB® was utilized to implement Singular value decomposition (SVD) and calculate the k-reduced approximate matrix. SVD is available in MATLAB® as a built-in function. Since the number of dimensions retained in LSA is an empirical issue [26], for this research, we retained dimensions 2-101 as is customary.

5. ***Measure semantic coherence***

We used two methods to study the semantic coherence to design team communication. The first method was adopted from the knowledge convergence method [8]. For clarification purposes, we refer to this as "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 $n \times 1$.

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

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 C_i of each speaker.

$$C_i = \frac{\sum_{v=1}^{v_i} S_{v,i}}{n_i} \tag{2}$$

where $S_{v,i}$ represents the singular vector of the *v-th* utterance of speaker i, n_i is equal to the number of speakers in the team.

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

$$\cos(C_i, C_g) = \frac{C_i \cdot C_g}{\|C_i\|\|C_g\|} \tag{3}$$

The second method is termed "semantic coherence between team members". A new metric was proposed to compute the semantic coherence between any two team members. We speculated that a high level of semantic coherence between team members indicates that the two members' communication are very similar, which in turn may indicate very similar understandings of the problem. This may be equivalent to "groupthink" and hinder 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". This method is shown below:

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

$$C_i = \frac{\sum_{v=1}^{v_i} S_{v,i}}{n_i} \tag{4}$$

2) Compute the cosine similarity between any two speakers where C_i is the centroid of speaker i and C_k is the centroid of speaker k.

$$\cos(C_i, C_k) = \frac{C_i \cdot C_k}{\|C_i\|\|C_k\|} \tag{5}$$

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 produce innovative ideas, and participate equally in decision-making process.

2.2 Applying LSA to Chinese Language

As the experimental condition in this study took place with Chinese speakers, we describe in detail how LSA is applied to Chinese. Chinese language has its own distinctive characteristic - the minimum unit is a character rather than a meaningful word; thus there are some differences between text processing of Chinese language and that of English. The most significant difference is that we need extra text analysis to parse Chinese sentences into meaningful words that may be comprised of multiple characters. Here, we illustrate how to construct a word-by-document matrix for Chinese language. A short discussion of one expert team was extracted from conceptual design stage. The team members were conducting a market analysis for a cycling device. The authors attach an English translation of the discussion.

D: 嗯，东亚的市场我想和欧美的市场完全不一样的，欧美的市场 ，呃，可能娱乐的成分要多一些，东亚的话呢，生活水平啊，实用性比较多一点。所以我们说针对东亚的市场而不是欧美的市场，基于这个市场我们来。 D: I think the East Asian market is totally different from the European and the American market. There may be more entertaining elements, er, in the European market, while more functional elements in the East Asian market, (considering) the living standard. So we say we should focus on the East Asian market instead of the European and the American market. Based on this we (design our product).
B: 这方面是要考虑的，我觉得他是有个侧重点的，嗯，他侧重的是东亚年轻人的这一块。 B: We need to consider this. I feel it has an emphasis. Em, it emphasizes the market for East Asian young people.
A: 所以这个东西不光要有实用性, 还要有时尚性。 A: So this product must have style besides functionality.
D: 嗯，所以我们来看看这个产品是时尚性多一点还是实用性多一点。 D: So let's see if the product should focus more on style or functionality.
B: 从我的想法来看, 东亚从整个年轻人来讲，呃，大家整体的一个趋势还是比较时尚的。 B: In my opinion, the trend for East Asian young people, er, as a whole is style.
C: 时尚、轻便，比方说，嗯，我离地铁站有一公里，我用这个车到地铁站，拎上地铁，下了地铁之后呢，骑这个车到公司，上海这个车蛮多的。 C: Style, easy to carry. Let's say for example, em, the distance between my (home) and the train station is 1km. I take this cycling device to the station, carry it onto the train. After I get off the train, I take it to the company. There are many cycling devices like it in Shanghai.

The short discussion was processed by the Chinese language processor ICTCLAS [24] to segment the sentences into words and assign part-of speech to each of them. This software uses the corpus annotation set developed by Peking University Institute of Computational Linguistics [27]. The annotation set includes 19 annotations for describing basic type of Chinese words. The results are shown below. Most of the meaningful words consist of two or more than two Chinese characters.

D: 嗯/e ，/w 东亚/n 的/u 市场/n 我/r 想/v 和/c 欧/j 美/j 的/u 市场/n 完全/a 不/d 一样/a 的/u ，/w 欧/j 美/j 的/u 市场/n ，/w 呃/e ，/w 可能/v 娱乐/v 的/u 成分/n 要/v 多/m 一些/m ，/w 东亚/n 的/u 话/n 呢/y ，/w 生活/v 水平/n 啊/e ，/w 实用/v 性/k 比较/d 多/a 一点/t 。/w 所以/c 我们/r 说/v 针对/p 东亚/n 的/u 市场/n 而/c 不/d 是/v 欧/j 美/j 的/u 市场/n ，/w 基于/p 这/r 个/q 市场/n 我们/r 来/v 。/w
B: 这/r 方面/n 是/v 要/v 考虑/v 的/u ，/w 我/r 觉得/v 他/r 是/v 有/v 个/q 侧重/v 点/n 的/u ，/w 嗯/e ，/w 他/r 侧重/v 的/u 是/v 东亚/n 年轻人/n 的/u 这/r 一/m 块/q 。/w
A: 所以/c 这个/r 东西/n 不光/c 要/v 有/v 实用/a 性/n ,/w 还要/v 有/v 时尚/n 性/n 。/w
D: 嗯/e ，/w 所以/c 我们/r 来/v 看看/v 这个/r 产品/n 是/v 时尚/n 性/k 多/a 一点/t 还/d 是/v 实用/a 性/n 多/m 一点/t 。/w
B: 从/p 我/r 的/u 想法/n 来/f 看/v ，/w 东亚/n 从/p 整个/b 年轻人/n 来讲/u ，/w 呃/e，/w 大家/r 整体/n 的/u 一个/m 趋势/n 还/d 是/v 比较/v 时尚/n 的/u 。/w
C: 时尚/n 、/w 轻便/a ，/w 比方/c 说/v ，/w 嗯/e ，/w 我/r 离/v 地铁站/n 有/v 一/m 公里/q ，/w 我/r 用/p 这个/r 车/n 到/v 地铁站/n ，/w 拎/v 上/m 地铁/n ，/w 下/v 了/u 地铁/n 之后/f 呢/y ，/w 骑/v 这个/r 车/n 到/v 公司/n ，/w 上海/n 这个/r 车/n 蛮/d 多/a 的/u 。/w

The meaningful words with part of speech information were used to construct the word-by-document matrix. In our study, essential words were retained, including nouns (n), verbs (v), adjectives (a), adverbs (d), measure words (q), localizer (f) morpheme (g) space words (s) short form words (j), idioms (l) and distinctive words (b). Only the words that appear more than twice in the utterances are extracted to form the word-by-document matrix. The resulting matrix is shown below. Please note that some of the words do not have a corresponding English translation, but they are meaningful elements in Chinese.

	1	2	3	4	5	6
东亚/n (East Asia)	3	1	0	0	1	0
市场/n (market)	6	0	0	0	0	0
欧/a (European)	3	0	0	0	0	0
美/a (American)	3	0	0	0	0	0
要/v (need)	1	1	1	0	0	0
多/a (more)	1	0	0	1	0	1
说/v (say)	1	0	0	0	0	1
个/q	1	1	0	0	0	0
来/v	1	0	0	1	0	0
有/v (have)	0	1	2	0	0	1
年轻人/n (young people)	0	1	0	0	1	0
实用/a (functional)	0	0	1	1	0	0
性/n	0	0	2	1	0	0
时尚/n (style)	0	0	1	1	1	1
还/d	0	0	0	1	1	0
地铁站/n (train station)	0	0	0	0	0	2
车/n (cycling device)	0	0	0	0	0	3
到/v (arrive)	0	0	0	0	0	2
地铁/n (train)	0	0	0	0	0	2

3. EXPERIMENTAL DESIGN

The data for study two was obtained from the collaborative product design team study [28] from the 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.

3.1 Subjects

The background information of the participants is shown in Table 1.

Table 1. Background information of participants

t	Code	Sex	Age	Experience (years)	Job Title
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
	2-D	Male	33	11	Product Design Leader
3	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. Team members inside one team knew each other well.

3.2 Task design and procedures

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

3.3 LSA analysis

The three teams communicated in Chinese. Native speakers transcribed their conversations with technical proficiency. The transcriptions of the three product design teams' verbal communication were subject to LSA analysis following from step 2 to step 5. In step 5, both metrics were computed to measure the semantic coherence.

3.4 Design process and design outcome evaluation

Design process evaluation criteria in this research were built upon the team effectiveness evaluation questions suggested by Payne [29]. Eleven questions were chosen to assess several aspects of the team process. Two human factors specialists from Centre for Human Factors and Ergonomics, Nanyang Technological University rated each team based on the 11 questions. 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, based on documentation and sketches produced by each design team. They were able to access the video recordings. Eleven assessment criteria were used to measure the overall design outcomes. Moreover, the experts gave assessment to the design outcome of each design stage. The 11 evaluation criteria for design process quality are: goal clarity, participation, decision-making, communication, information sharing, collaboration, feedback, conflict, mutual support, productivity, continuous improvement. The 11 evaluation criteria for design product outcome are: marketability, profitability, advancement, creativity, structure of product sub-systems, functional parameter of product sub-systems, preliminary assembly blue print, detail design of product parts, procurements, material and processing technology, final assembly blue print.

4. RESULTS AND DISCUSSION

4.1 Semantic Coherence in Design Team One

Figure 1 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 between each participant and the group's semantics could be considered rather poor.

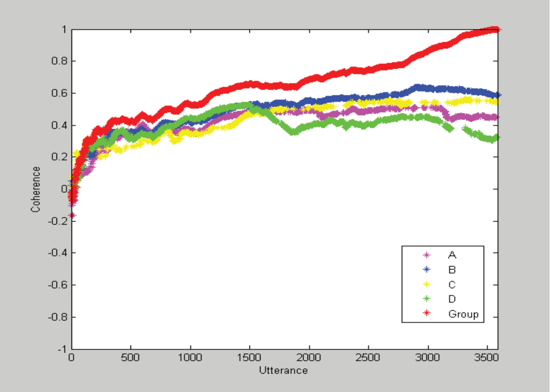

Figure 1 Semantic Coherence to Group Centroid of Team One

Table 2 summarizes the maximum semantic coherence between team members of team one. We can see that none of the semantic coherence between team member's values was above 0.15. Half of the coherence scores were negative. This confirmed the observation, based on both metrics, that the team was both unable to reconcile viewpoints and the participants were not communicating well with each other. These results suggest a poor process quality and a likely poor product quality.

Table 2 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

4.2 Semantic Coherence in Design Team Two

The semantic coherence to group centroid of team two is shown in Figure 2. The semantic coherence to group centroid of team members A, C and D were fairly close and ended at around 0.7. These three team members dominated the running semantic coherence of the group. Speaker B in this team lagged behind and the upper limit of this participant's coherence was only 0.4. The language tracking of the team was considered rather good since the dominant team members' semantics tracked closely and the final individual to group semantic coherences were fairly high.

Table 3 shows the semantic coherence between any two team members. The semantic coherence between the three dominant team members, A, C and D were relatively high. On the contrary, the semantic coherence between speaker B and the other three were fairly low, even below zero. This may indicate that speaker B was not in concordance with the other team members or he could be a creative outsider. Both Figure 2 and Table 3 show that speaker B is not congruent with the rest of the team, but that, otherwise, the team is performing fairly well.

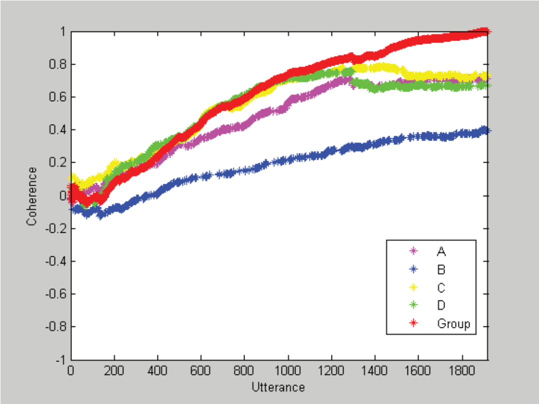

Figure 2 Semantic Coherence to Group Centroid of Team Two

Table 3 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

4.3 Semantic Coherence in Design Team Three

Figure 3 shows the running semantic coherence to group centroid of team three. The semantic coherence to group centroid of team members B and D were closely spaced and rapidly converged towards 1. Speaker C did not follow the group centroid, and the semantic coherence to group centroid ended at around 0.5. It is worthwhile to analyze closely the semantic coherence of member A given how closely this member tracks the group's semantic coherence. Speaker A's semantic coherence to group centroid was negative for nearly half of the conversation, as was the group's, and then began to increase and finally exceeded 0.4. Although Speaker A's semantic coherence was negative to start with, it was closely spaced with the group's running semantic coherence. This indicates that speaker A dominated the discussion at the initial stage of the design task and speakers B and D dominated the later conversations. Moreover, during the whole process, the team experienced some turns and the group's running semantic coherence showed a sharp change as well. Towards the end of the design task, their individual to group semantic coherences are higher than any of the other teams. In conclusion, the results showed that the language and knowledge tracking of the team were not perfect.

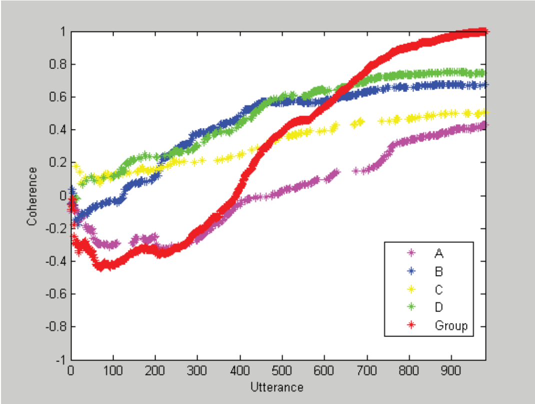

Figure 3 Semantic Coherence to Group Centroid of Team Three

Table 4 illustrates the semantic coherence between team members. The coherence values were moderately high, all above 0.4, which is higher than for the other teams. This result tempers the interpretation of Figure 3. The results of Table 4 suggest that the members are working well together between participants even though they do not all appear to be working well as a group. Instead, what is likely happening is that the members are playing their roles during the group situation, which thus makes the coherence lines in Figure 3 appear not closely spaced. These results are a possible example of a false negative illustrating the situation when a team does not appear to strongly work together although they are working well between team members.

Table 4 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

4.4 Comparison between Team Semantic Coherence and Experts' Evaluation

Table 5 presents a summary of the qualitative analysis of the teams based on their semantic coherence as well as experts' evaluation of design process and design outcome of the three teams. From the experts' evaluation, team three scored the highest in both design process and design product 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.

Table 5 Summary of Semantic Coherence Analysis and Expert's Evaluation

	Semantic coherence to group centroid	**Semantic coherence between team members**	**Design Process**	**Design Outcome**
Team one	Rather poor. 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 values was above 0.15. Half of the coherence scores were negative.	50.0	54.0
Team one	Rather good. The semantics of three team members converged closely (0.7) at the end. The semantic coherence of the fourth member was sparse.	The semantic coherence between the three dominating 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 three	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 pair of the four members was relatively high, all above 0.4	63.0	59.0

For team one, the results of the two semantic coherence metrics suggested 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, 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 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 coherence with the other members, and even a negative coherence with team member D. This indicated that person B was not "on the same page" with the team. A close examination of the transcripts of team two revealed that of the 1919 content-bearing utterances, person B contributed only 392 utterances, the least among the team members. Besides his lack of participation in terms of number of utterances, person B interrupted with the process of the rest of team. This interruption can be illustrated by 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 an accurate number

> 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.

The rest of the team ignored this suggestion and proceeded to compute the length of the parameter. This destructive influence of speaker B seemed to strongly affect the performance of team two, resulting in a relatively ordinary design process quality and poor design outcome quality. The experts gave team two an average 5 points for the design process. However, it scored the lowest in 10 out of 11 criteria, and performed the worst of the three groups in terms of design product 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 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 indicates 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 "negative" (i.e., divergent) 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 consistency between the two. Team three outperformed the other two teams in terms of both design process quality and design product outcome. Moreover, the creativity score of team three was at least 20% higher than that of the other two teams. This, combined with a review of the early parts of the transcript, confirmed our previous speculation that this team conducted brainstorming of design ideas at the beginning of the experiment.

In conclusion, we can see that the two semantic coherence metrics complement each other. By combining the two, we developed a more accurate way of characterizing the semantic coherence of the team and the team's process quality. Moreover, the results also showed that the semantic coherence to the group and between team members were more indicative of design process than design outcome, and that both metrics are needed to accurately indicate process quality. In our study, the level of semantic coherence of each team was consistent with the design process quality, but could not fully explain the variations in design product outcome quality.

5. CONCLUSION AND FUTURE WORK

The dynamic nature of design team results in studies on social behavior and cognition based on psychometrics, sociometry, computational linguistic techniques and so forth. Latent semantic analysis is able to extract the latent meaning in design communication and rapidly analyze a large number of design documents. The proposed method of "semantic coherence between team members" measured the similarity and semantic coherence between team members. It complemented the existing "semantic coherence to group centroid" metric. Together, both metrics offered a more accurate indication of design team process quality based on the semantic coherence of verbal communication, particularly when the semantic coherence to group metric is inconclusive. However, there is not enough information to justify that the new metric is able to detect phenomenon such as groupthink in team discussion due to the limited sample size and lack of close interrogation of the design teams' transcriptions. The decoupling of design process and design product outcome did give us a better understanding of the application of LSA to studying design team communication.

There are limitations of this research, and the results have to be viewed in the light of them. It is difficult to obtain access to experienced designers for these types of studies. In the experimental study, only 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 provide us predictive statistical evidence.

There are several opportunities for further research. We postulate that there exists an inverted U relationship between semantic coherence and design team performance, where extremely high levels of semantic coherence between team members indicates the members' understandings of the design are too similar, which may result in "group think" and thus poor process quality, while a low level or even negative level of semantic coherence between team members signifies the members are not "on the same page" at all, which is also a poor process outcome. However, due to the limited sample size, this relationship was not fully explored in this research. Further studies can be carried out to model this relationship by combining both qualitative and quantitative methods. The interaction between the two methods, 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 quantitative principles for indicators of team process quality. These rule-based principles would offer monitoring aids to design teams and their managers.

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