

# *The latent semantic approach to studying design team communication*

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*How does a team of designers come to construct knowledge about the artefact that they're designing? This question is the subject of intensive research on human behaviour in design employing methods including cognitive and psychometric evaluations and ethno methodological observations. Language-based communication has been argued to play a principal role although the structuring of communication as scaffolds for knowledge construction has never been measured directly. This article puts forth a method for studying design team communication that enables the direct measurement of knowledge construction. Latent semantic analysis (LSA) of language-based communication such as design documentation corpora and verbal communication reveals, from the local co-occurrence of vocabulary, coherence of thought and the formation of a socially held representation of the designed artefact. The results lead to the hypothesis that the similarity of language use bridges indirect relations among components of knowledge stored in each designer's mind, leading to a constructed shared mental representation of the designed artefact.*

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**A**s Tolstoy put forth in the first lines of *Anna Karenina*, 'All happy families resemble each other; each unhappy family is unhappy in its own way.' Tolstoy means to say that a confluence of factors leads to a happy family. The failure of any one of these factors may doom the family.

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Design teams fare similarly. Research into behavioural and cognitive factors that influence team success could be categorised by their disciplinary roots: cognitive psychology, organisational behaviour, and strategic management. Cognitive psychologists developed models of

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group cognition (Cannon-Bowers and Salas, 2001) based on extensive studies of groups of people performing pre-specified tasks. These models of the 'social mind' account for group cognitive activities such as learning and reasoning. Primarily focusing on the work place, organisational behaviour researchers describe a set of proximate behavioural factors which impact work performance premised on the concept of team mental models (Klimoski and Mohammed, 1994). The general thesis is that team effectiveness will improve if team members have an adequate shared understanding of the team's objectives, processes, and situation. For example, knowledge about tasks (i.e., who's doing what and how) should be distributed among team members. The strategic business management literature on new product development identified high-performance teams as a recurrent factor on the speed (measured in terms of time to market), likelihood of success, and productivity of new product development (Griffin, 1996). Behavioural characteristics of high-performance teams include a high level of interaction with other team members resulting in an interactive and iterative combining of perspectives (Dougherty, 1992), leadership, and cultural heterogeneity. This interactive and iterative combining of perspectives has been reconstructed through *post-hoc* reflections rather than direct assessment. In summary, as the aphorism goes, the recipe for successful teams is straightforward – communicate. Nonetheless, as numerous case studies of design in industry relate, even when the team possesses all the 'right' factors, success is not guaranteed. The artefact could be so technologically complex that not even optimal teamwork would suffice.

Despite the discrepancy that not all of the groups studied by the aforementioned research were engaged in designing, except for those reported by the strategic management research, these research contributions provide the social and technical perspectives to elucidate explanatory, predictive and diagnostic facets for understanding the behaviour of teams in general. While the methodologies may differ, the goals of the research – to understand what factors influence a team's high performance, to optimise the composition of teams (Wilde, 2000), and to predict the performance of individuals placed in teams (Lucius and Kuhnert, 1997) – are common. The problem though is that the methods (e.g., protocol analysis, psychometric evaluations, sociometry) by which these factors were derived are essentially inaccessible to design teams and design team managers. For sure, the methods have limited evaluative impact on dealing with the nuances of communicative interactions as they occur and to provide constructive in-process improvement.

We developed the latent semantic approach to studying design team communication as a reliable, transparent, and scalable method by which design team communication could be analysed to ‘take a pulse’ of the state of the design team. What we found is that the latent semantic approach offers an apparatus to model congruent thinking and distributed knowledge representation in design teams.

The aim of this article is twofold. First, the article provides a summative review of our research in developing the latent semantic approach for studying design team communication. As a result of empirically observed discoveries and the successes of the approach, the second aim is to suggest a different hypothesis to explain the question posed in the abstract – how a team of designers come to construct knowledge about the artefact that they’re designing. The hypothesis is that language (and the meaning of words) is a facilitator to bridge gaps of knowledge between what individual team members know and the larger body of experience held by the team. How communication was structured over time accounts for transforming representations of the designed artefact from individual ‘object worlds’ to a ‘shared world’. The outcome is that team members construct a socially held representation of the designed artefact. A primary mechanism by which this knowledge is expressed and then constructed is language-based communication. Diagrams and visual models clearly play a vital role; nonetheless, the popular game *Pictionary*, in which players attempt to guess words from pictures, highlights the difficulties of designing and communicating in teams when language is absent. Sonnenwald (1996) clarified this point and further described the ‘boundary spanning’ communication roles that team members undertake to facilitate knowledge sharing and exploration and task coordination.

The hypothesis shares ideas from Gordon Pask’s conversation theory (1975), namely that the construction of knowledge occurs through conversations about a subject matter, which serve to make knowledge explicit. For design teams, where cognitive activities are distributed across social spaces, the structuring of their language to communicate affects the cognitive properties of the group.

The premise of the article is that the psychological similarity between each designer’s own mental representation and the socially held representation of the designed artefact is reflected in the semantic coherence between words in the way they co-occur in dialog and other language-based communication. The congruence of collective mental

functioning facilitates the coordinated action that is required for successful team-based design.

In the following sections, the article describes experiments on language-based communication – that is, asynchronous and synchronous communication – using latent semantic analysis (LSA). We begin by discussing why LSA is a suitable computational linguistics tool for modelling the ‘psychological similarity between thoughts’ based on language (Landauer and Dumais, 1997). Then, the article examines the research in applying LSA for studying design team communication, and presents a new analysis of the data.

### *1 Latent semantic analysis*

In order to study how language-based communication contributes to the formation of the group’s socially held representation of the designed artefact, a computational linguistics tool is required to link empirically the existence and choice of individual words to terminological conventions. Latent semantic analysis (LSA) (Landauer et al., 1998) is such a computational linguistics tool. The baseline theory for LSA is that by looking at the entire range of words chosen in a wide variety of texts, patterns will emerge in terms of word choice as well as word and document meaning. LSA is unique in its method to analyze text; in its analysis, there is no consideration of word order or syntax. The principal advantage of LSA over other computational linguistics techniques such as lexical chain analysis and anaphora resolution is LSA’s examination of context instead of individual word meanings. All other computational linguistics tools degrade in performance when the data set is noisy or semantic understanding is insufficient. Oral and informal written communications tend to be especially ‘noisy’. Examining context removes obfuscation created by ‘noise’ in the oral and written communication, and scales up to deal with very large corpora. The track record for LSA as a computational tool *and* model of language acquisition and acquired knowledge is significant. LSA has been applied to a wide range of problems in identifying the contextual meanings of documents for full-text information retrieval (Foltz et al., 1998), assessing learning (Landauer et al., 2000; Shapiro and McNamara, 2000), modeling acquired knowledge (Landauer and Dumais, 1997), and characterising the performance of design teams (Dong et al., 2004).

LSA is based on the mathematical technique of singular value decomposition (SVD), an optimal approximation, in the least-squares sense, of a matrix. The mathematical procedure for LSA is to apply

SVD to a word-by-document matrix  $\mathbf{X}$  of dimension  $n \times m$  ( $n$  words;  $m$  documents;  $m < n$ ) resulting in three component matrices using the relationship  $\mathbf{X} = \mathbf{U}\mathbf{S}\mathbf{V}^T$  where  $\mathbf{U}$  ( $n \times m$ ) and  $\mathbf{V}$  ( $m \times m$ ) are the left and right orthonormal singular matrices, respectively, and  $\mathbf{S}$  ( $m \times m$ ) is the diagonal matrix of singular values. For verbal dialog, each utterance could be treated as a document. If the singular values in  $\mathbf{S}$  are ordered descending by size, the first  $k$  largest may be kept and the remaining smaller ones set to zero. The product of the resulting  $k$ -reduced matrices is a matrix  $\tilde{\mathbf{X}}$ , which is approximately equal to  $\mathbf{X}$  in the least-squares sense and of the same rank. That is,  $\tilde{\mathbf{X}} \approx \mathbf{X} = \mathbf{U}\mathbf{S}\mathbf{V}^T$ . This is often called the  $k$ -reduced matrix. A detailed example of latent semantic analysis is provided by [Dong et al. \(2004\)](#).

### *1.1 The latent semantic approach*

While the text processing and mathematical components of LSA are well-understood, the innovations in the latent semantic approach have been in establishing directly measured metrics and imputed visualisations based on the  $k$ -reduced matrix. The latent semantic approach to studying design team communication proceeds as follows:

- 1 Capture the language-based communication produced by the design team.
- 2 Use a natural language parser (such as JavaNLP [<http://www-nlp.stanford.edu/javanlp/>]) to extract words and phrases from the corpora.
- 3 Create a word-by-document matrix which counts the frequency of occurrence of each word in each document from Step 2.
- 4 (Optional) Use log-entropy scoring on the matrix from Step 3 to filter the word list to a set of discriminating terms. A useful cut-off is to include terms with an average log-entropy greater than or equal to the mean log-entropy.
- 5 Apply LSA (singular value decomposition) on either the raw frequency or log-entropy matrix. SVD is available in most mathematical computing software. For extremely large matrices (i.e., on the order of a million rows or columns), use SVDPACK ([Berry, 1992](#)).
- 6 Compute the  $k$ -reduced approximation of the matrix. It has been experimentally determined in various research projects that retaining up to the first 300 most significant singular dimensions provides the best approximation of the ‘latent semantics’. For our analyses, we retained dimensions 2–101.
- 7 Compute metrics and visualisations (see individual studies below) based on the  $k$ -reduced matrix.

To establish the empirical evidence to address the original question, we examined language-based asynchronous (e.g., design documentation, e-mail) and synchronous (e.g. verbal conversations, online chat) communication.

## 2 Studies

### 2.1 Congruent communication

In the first portion of our research, we postulated that the overlap in word choice in designers' language-based communication characterises a common frame for the design team. Since the documents were authored by various team members, each contributed individual knowledge to the artefact's function, behaviour and structure. Words and phrases used by designers during the design process contributed to a narrative which captures, among many items, personal experience, functional specifications, negotiations, and resolutions. Design specifications and solutions in text relate more than numbers and formulae; they reflect the conflicting interests and resulting reconciliation and shared agreements of the design team members. The semantic coherence of their language-based communication is a metric of the congruency of their joint communication.

We computed two metrics, the Variation in Semantic Choice (Equation 1) and Semantic Coherence (Equation 2), to assess congruent communication. 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  $i$ .

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Variation in Semantic Choice

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

Semantic Coherence

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


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The Variation in Semantic Choice metric indicates the closeness of each document to the average document. We call the average document the 'concept centroid'. The centroid is an abstract semantic representation of the concept of their design, that is, the constructed socially held

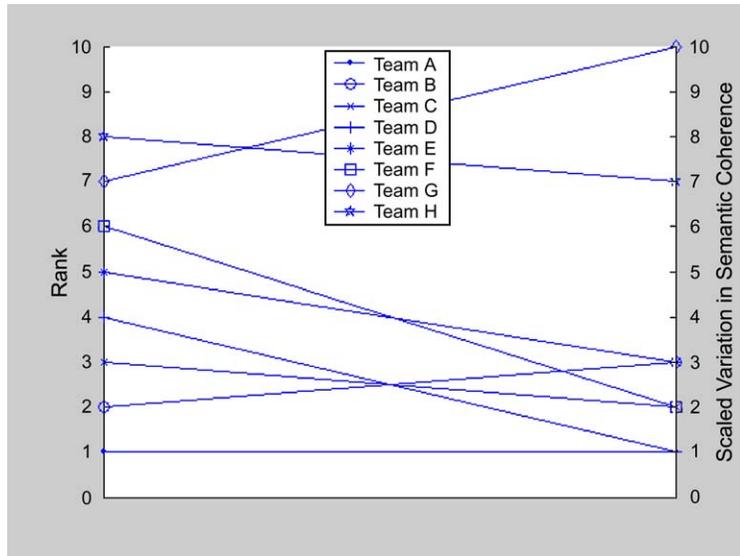
representation about the artefact that they're designing. Mathematically, the centroid is computed by finding the average value of each row in the  $k$ -reduced matrix. The centroid should be of dimension  $n \times 1$ .

The Semantic Coherence metric measures the semantic similarity of each document, that is, the similarity with which all designers represent individual knowledge about the artefact through written text.

Studies of the asynchronous communication were based on design documentation from student product design teams. The documents were collected over a 15-week period and consisted of e-mail, mission statements, customer feedback, product testing and engineering memos, presentation materials, and personal and group reflections on the team's execution of the process and product at each stage of the product development process. The semantic space was constructed by collecting on the order of  $10^2$  documents per team where each document contained on the order of  $10^1$ – $10^3$  words.

The projects were typically consumer products with low complexity. While the students self-selected the projects, the academic staff guided the students in choosing products to enable learning the product development process and engineering design rather than focusing on specific technological challenges. To ascertain the congruent communication relative to each team, we combined all documents and words into a single matrix before computing the SVD and the  $k$ -reduced matrix. Then, we extracted the appropriate documents for each team to calculate the metrics. We calculated these metrics for the teams and then ranked the teams based on the metrics. We compared these computed team rankings to rankings by expert (professional product designers and academic staff) assessments of the final product and team process. Based on these metrics, we found empirical evidence to relate *low* variation in semantic choice and *high* semantic coherence of design documentation to the quality of the outcome (i.e., high quality product and process) and as a potential measure of shared understanding in design (Hill et al., 2002). Figure 1 illustrates the relationship between the expert ranking and a scaled value of the variation of semantic coherence calculated for each team. The scaling was calculated as 10 times the fraction of the respective team's variation in semantic coherence to the highest variation for the data set. We note in particular that the poorest performing teams, Teams G and H, had a scaled variation in semantic coherence more than twice the others. The actual numeric values of semantic coherence will vary depending upon the teams and the type of design project (e.g., routine, innovative, breakthrough). The important

Figure 1 Relationship of faculty rank to scaled variation in Semantic Coherence



aspect to note from Figure 1 is the distinguishable difference in semantic coherence between rather well-performing teams (A–F) and poorly-performing teams (G and H).

We then studied the time variation in textual coherence by computing the cosine similarity (Equation 3) between design documents  $d_p$  and  $d_q$  adjacent in time as each document was written.

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Cosine similarity 
$$\cos(d_p, d_q) = \frac{d_p \cdot d_q}{\|d_p\| \|d_q\|} \quad (3)$$

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We found a positive correlation between positive outcomes and *variation* in textual coherence between design stages (Song et al., 2003). That is, the occurrence of increasing textual coherence with cycles of divergence during the design process appeared desirable, with iterative broadening and narrowing of the design possibilities, and an iterative reconciliation of design interests and conflicts towards a set of shared agreements. Further corroborating our findings, Martin and Foltz (2004) also found that LSA analyses of discourse can accurately predict team performance and that there was a positive correlation between semantic similarity and team performance in their study of a simulated military mission.

The observed results allowed us to conclude that there is a relation between semantically coherent documents and positive design outcome. Despite the relatively brief period of the design projects studied with respect to industry projects, we may extrapolate that teams with coherent communication at the end of design stages are more likely to have better outcomes than teams with incoherent communication. The empirical evidence corroborates the popular aphorism ‘on the same page’ in the sense that each designer’s ‘page of documentation’ appears similar to the others’. Either of the above metrics could be calculated at gate reviews to assess the level of congruent thinking in relation to prior projects at the same stage of development or to prior stages. *More significantly, we believe the concept centroid provides a device to characterise a socially held representation of the designed artefact by which team member’s representations may be compared.* When the distance from the socially held representation was nearer to each designer’s representation, the evidence stated that a successful design outcome was more likely.

In the synchronous communication studies, transcriptions of verbal discussions in which a group of designers were asked to design an artefact were examined. The first transcription was from the mountain bike backpack design problem at the 1994 Delft Protocols Workshop (Cross et al., 1996). The transcript contains 2190 ‘raw’ utterances among three designers over a 118-min period. Excluding utterances containing only interjections such as ‘mmm’ and ‘oh,’ there were 1662 content-bearing utterances. The utterances may consist of multiple complete sentences or incomplete thoughts. The second set comes from the Bamberg Study (Stempfle and Badke-Schaub, 2002) of design thinking of three teams based on their language communication.

Studying synchronous language-based communication turned out to be more problematic. A meaningful computation of variation in semantic choice and semantic coherence is not possible. For verbal communication, each ‘document’ is really a set of short utterances, most of which consist of too few words to establish large enough contexts for LSA. Another approach is required. Instead, we computed aggregate average semantic coherence between utterances which were one utterance away, two utterances away, and so forth. The presumption was that if the language was coherent, then there should exist a mostly orderly mapping between semantic coherence and distance between utterance boundaries. That is, utterances close together should be similar, utterances further apart less so. The computational analyses revealed two patterns of conversations in the data sets: one in which the speakers

built upon each other's utterances resulting in an increased level of coherence and one in which there was little in the way of building upon each other's expressions of ideas (Dong, 2004). What is significant about the findings is not just the patterns of communication in the design teams, but that the successful teams' conversations built upon each designer's representations of knowledge and ideas as expressed through lexicalized concepts. *The constructive conversations were the ones in which components of knowledge stored in each designer's mind, and expressed through conversation, augmented and amplified coherent discussions.* Talking and exchanging ideas lead to the construction of the socially held representation.

## 2.2 Knowledge convergence

While the above analyses provide a metric for the existence of a socially held representation, the analyses do not illustrate the *social process* of constructing the representation. The strategy here is to examine the construction as an emergent property based on the acquisition of a common set of semantics in language-based communication.

We call this method the knowledge convergence method. This technique computes how one's language use becomes similar to the group's overall language. This technique indicates, in a conservative assertion, an acquisition of common semantics. The bolder assertion is that the acquisition of semantics reveals an internalization of knowledge, that is, the social transference of knowledge. This analysis is based on the following algorithm:

- 1 Compute the group's concept centroid as described above.
- 2 Extract from the  $k$ -reduced word-by-document matrix the columns (i.e., documents or utterances) corresponding to each author/speaker.
- 3 Compute the cosine similarity (Equation 3) between the group's centroid and each author's/speaker's running average centroid. That is, for each new document/utterance that has been contributed by an author/speaker, compute the updated centroid for the author/speaker. Then, re-calculate the author's/speaker's cosine similarity to the group's centroid. Repeat this calculation for the group's emerging concept centroid, that is, compare the group's current centroid to the final centroid.

If, in Step 1, the group's centroid is replaced by any one or more speaker's centroid, then one could also compute the language (knowledge) acquisition between any set of speakers.

Knowledge convergence is visualised as ‘Knowledge Tracking’ to illustrate how closely each speaker’s semantics tracks the group’s semantics. We could speculate that the optimal knowledge tracking for each author/speaker should be rather close together and converge towards the group’s centroid. This pattern would indicate congruence with and contributions to the group’s semantics. In the graphs of Figures 2–6, these are indicated by the separation between each speaker’s semantic coherence and the convergence and progression towards 1 of each speaker’s semantic coherence to the group’s semantics. At the extremes, a constant knowledge tracking of 1 would indicate that no new knowledge is being added – clearly undesirable repetitions of the same ideas – as is the other extreme, a knowledge tracking of 0, which would indicate dialectic semantics. Perhaps there are tangential semantics or novel ideas expressed, but a well-performing design team should avoid fixation.

For the asynchronous communication (design text), we show the data for Team A (Figure 2), high performing, and Team H (Figure 3), low performing corresponding to the same data set as before. Immediately, one notices that Participant A and Participant S drove the communication of concepts for Team A (Figure 2). Also, their knowledge tracking quickly progressed towards 1. The other participants made relatively fewer contributions; Participant T and Participant B were often in conflict with the team. This result is consistent with the team’s

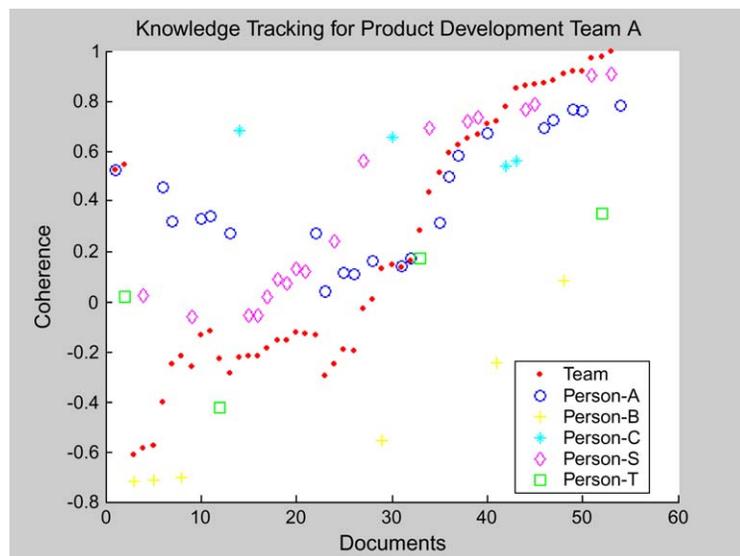
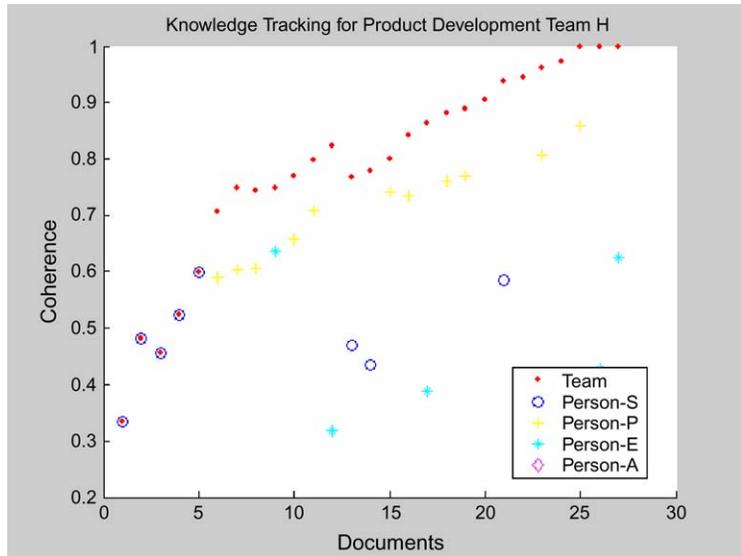


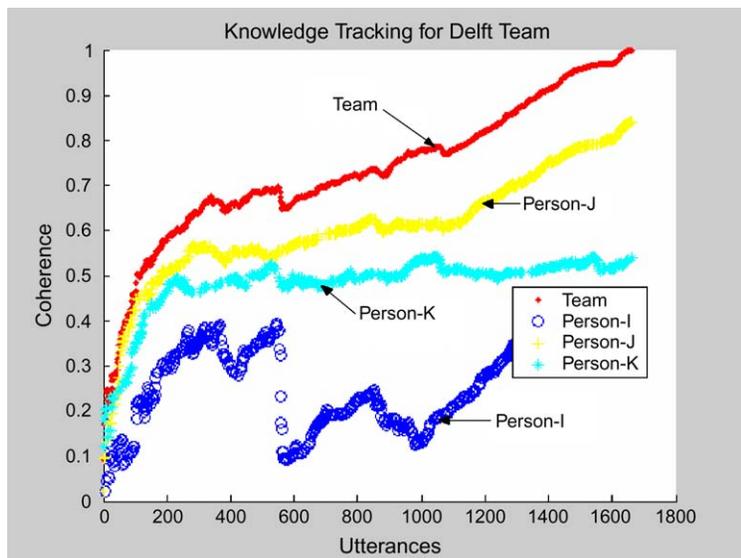
Figure 2 Knowledge tracking for ‘High Performing’ product development team

Figure 3 Knowledge tracking for 'Low Performing' product development team



post-mortem statements which noted that a few members did the majority of the work and that Participant T 'marched to [a separate] drum'. Conversely, Person C always seemed to agree with the team, having a coherence no less than about 60%. One team member described this person as the classic 'yes-man' who was generally 'not strongly opinionated on any subject' and 'goes along with general group

Figure 4 Knowledge tracking for Delft team



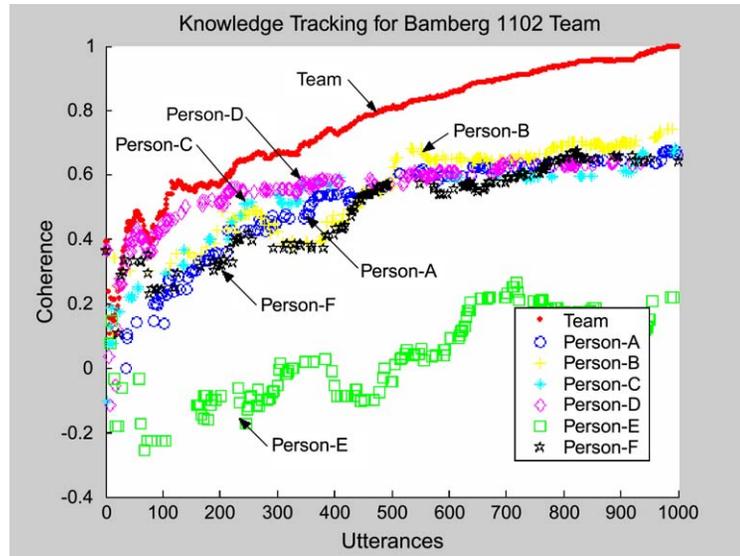


Figure 5 Knowledge tracking for Bamberg 1102 team

decision'. Thus, there is agreement between the computational results based on language and *post-hoc* reflections by the teams on the team's and individuals' behaviour.

For Team H (Figure 3), only one team member (Person P) drove the project, often in conflict to the ideas of the other team members, which led to this team's low overall semantic coherence as reported earlier, and

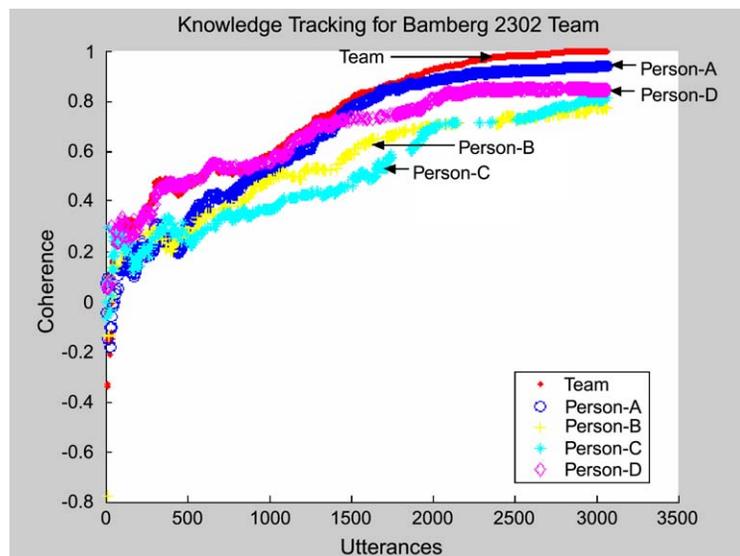


Figure 6 Knowledge tracking for Bamberg 2302 team

poor performance. In their post-mortem reflections, this team wrote that their problems were ‘rooted in the fact that we are struggling with a product concept. If we had a clear-cut vision, I think we would be clear sailing.’ Eventually, the lack of ‘vision’ manifested itself in a fragmented team. While a discord such as this would be simple to detect in a real situation, it is worthwhile to note how the knowledge convergence method ‘picks up’ the disconnect in their knowledge convergence.

We examined knowledge convergence on the same synchronous communication data sets as before. The well-performing Bamberg 2302 Team (Figure 6) demonstrates perhaps the ideal knowledge tracking. The graphs of speaker semantic coherence are closely spaced and rapidly converge towards 1, and at least exceeding 70%. Whereas for Bamberg 1102 Team (Figure 5), the limit of knowledge tracking was 60%, and for the Delft Team (Figure 4), it was less than 50% for two team members (I and K) and approaching 80% for one (J). For the Delft Team, Person J appeared to drive the direction of the communication whereas Person I and K neither strongly incorporated nor followed the team’s semantics. This is consistent with the qualitative profile of the team in which Person J has been described as the ideas person. This pattern also manifests in the Bamberg 1102 Team for Person E. This low level of knowledge tracking for Bamberg Team 1102 Team is consistent with the observation (Stempfle, 2004) that this team exhibited a lack of common understanding.

We can generalise from these results that knowledge convergence *should happen* in design teams, and, for successful teams, it does occur. The convergence phenomenon is evident in both synchronous and asynchronous communication. Social interaction theory (Adams, 1967) posits that consensus, the sharing of common values, interests and attitudes, and ‘positive concern’, coupled with long-term involvement and continuing interest, account for cohesiveness within a social network. When one of these breaks down, disharmony occurs possibly resulting in the break up of a consensual group. Examining knowledge convergence is one way not only to look at the acquisition of a common semantics and the process of constructing the socially held representation but also team cohesion, or how the team’s cohesiveness abets the formation of a socially held representation. LSA maps out the coherence of meanings of a series of words and how language use models knowledge acquisition and representation. *Team communication reflects the formation of mutual expectations and shared understandings.*

### 3 Conclusions

Our experiments on language-based communication based on the latent semantic approach reveal that the construction of a socially held representation is an emergent phenomenon that is, in part, driven by language-based communication. We found that the structuring of language-based communication over time played a transitive role in the formation of their socially held representation. We believe this socially held representation is a candidate for characterising *shared understanding in design*, that is, the existence of and agreement by the design team of congruent thinking regarding the product concept.

What is noteworthy about the experimental data set is the diversity, in the sense of design methodologies and expertise, of the design teams studied. Unfortunately, we do not have data about the individual designers in these studies and how their psychosocial profile, technical expertise, or teamwork skills influenced the operation of the team. Perhaps this point is moot, though. After all, in authentic design situations, design team formation is based on personnel availability and skills required. If the relation between language-based communication and semantic coherence and knowledge convergence could be measured and quantified, then mechanisms could be brought to bear to rectify obstacles.

Perhaps of more significance is that the ‘concept centroid’ could legitimately be construed as the design team’s socially held representation of the product that they’re designing. Developing a research apparatus to study the behaviour and to detect higher-level cognitive phenomena of team-based design is extraordinarily complex. The latent semantic approach to studying design team communication enables us to impute the design team’s socially held representation to their structuring of language. The methods described in this article demonstrate how to decode from design teams’ language-based communication an abstract semantic representation of the product they’re designing. As such, the latent semantic approach offers an attractive quantitative and scalable mechanism to research cognitive activities in design which are distributed across social spaces and mediated through language.

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