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QUANTIFYING COHERENT THINKING IN DESIGN: A COMPUTATIONAL LINGUISTICS APPROACH

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Abstract. Design team conversations reveal their thinking patterns and behaviour because participants must communicate their thoughts to others through verbal communication. This article describes a method based on latent semantic analysis for measuring the coherence of their communication in a conversation mode and how this measurement also reveals patterns of interrelations between an individual's ideas and the group's ideas. While similar studies have been done on design documentation, it was unclear whether computational techniques that have been applied to communication in text could be successfully applied to communication in a conversational mode. Transcripts of four engineering/product design teams communicating in a synchronous, conversational mode during a design session were studied. Based on the empirical results and the proposition that a team's verbal communication offers a fairly direct path to their thinking processes, the article proposes the link between coherent conversations and coherent thinking.

1. Introduction

1.1. VERBAL COMMUNICATION IN DESIGN

Social activities such as information exchange, compromise and negotiation figure prominently into phenomenological descriptions of design. The field of social cognition in design studies these social activities and their reciprocal influence on a design team's ability to create collective sense-making of the function, behaviour, structure and meaning of a product. Knowing how teams develop a shared, organised understanding and mental representation of knowledge about the designed artefact is critical for educating designers and for building design support environments.

One of the accepted methods for studying and understanding social cognition in design is the observation of designers (Lawson 1997). In design teams, because designers must communicate their thoughts to others, verbal communication offers a fairly direct path to the thinking processes of designers. "Think aloud" transcripts present a vehicle for peering into the thinking processes occurring during designing. The widely adopted method of verbal protocol analysis converts the "think aloud" transcripts into data (Ericsson and Simon 1993). The methodological roots for a rich body of literature on the cognitive processes of designers lay in verbal protocol analysis (Cross et al. 1996).

Recently, there has been the growing recognition to understand design in group situations. This appreciation has led to more in-depth analyses of design groups, that is, designers working together rather than individual designers working alone. Analyses of design team discussions using protocol analysis have led to interesting insights into the thinking behaviour of design groups such as strategies for reaching shared understanding (Valkenburg and Dorst 1998) and the patterns of basic cognitive processes in design groups (Stempfle and Badke-Schaub 2002). Computational studies of design team documentation (communication in text) illustrated the link between textual coherence and shared understanding (Hill et al. 2001), team performance (Dong et al. 2004), and variations in the design direction that a design group may pursue over a long period of time (Song et al. 2003). Being able to deduce aspects of design team behaviour automatically from their ongoing conversations would have a beneficial impact on studies in design workspaces which have recognised that verbal dialog constitutes a major part of design session activity (Tang and Leifer 1998) and advanced design research laboratories (Milne and Winograd 2003).

Increasingly, design teams rely on computer-mediated communication and collaboration tools such as email, chat, bulletin boards, "blogs" and virtual environments. Human based protocol studies would be unable to scale to the volume of information and communication generated by designers in real-world settings. Could computational methods assist in seeing the "haystacks" of behaviour before humans go about finding the "needles?" There is also an increasing call to encourage an ethic of self-reflection (Schön 1987). Placing teams under the watchful eye and lens of social science researchers, while of theoretical analytical value, may offer little for constructive in-process improvement. Could autonomous agents with the capability to assess the team communication supplement or confirm the teams' own awareness of breakdowns in communication?

This article concerns with the broader question of how cognitive processes during design could be assessed computationally, that is without reliance on hand coded protocol analysis. The approach taken to address one aspect of this question, coherent thinking in design teams, is based on computational linguistics. The premise of the article is that the psychological similarity between thoughts is reflected in the semantic coherence between words in the way they co-occur in dialog and other language-based communication. Latent semantic analysis (LSA) is a computational linguistics tool which provides one way to model this "psychological similarity between thoughts" based on language (Landauer 1999). The article demonstrates how to extend latent semantic analysis to analyse design communication in a conversation mode and develops metrics to measure the duration of coherent discussions in design teams. Based on the theory of LSA as a representation of knowledge (Landauer and Dumais 1997), the article proposes the alignment between coherent conversations and coherent thinking in teams.

For the purposes of this research, coherent thinking is not equated with thinking alike. That would leave the notion of coherent thinking at the level of "groupthink." Instead, coherent thinking is characterised by the alignment of thoughts among the design team participants that leads to the joint construction of knowledge about the designed artefact. Second, the article assumes that the designers' conversation is goal-oriented. They are not just "chatting," but are, for example, resolving a problem or cooperatively designing an artefact. The remainder of the article describes the computational linguistics method and what the empirical results imply about the coherent thinking of the design teams.

2. Methodology

2.1. LATENT SEMANTIC ANALYSIS IN DESIGN RESEARCH

Latent semantic analysis (LSA) (Landauer et al. 1998) is a text analysis method that characterizes the semantic similarity between words in texts using a high-dimensional semantic space. The mathematical foundation for LSA lies in singular value decomposition (SVD), a matrix approximation method for reducing the dimensions of a matrix to the most significant vectors. 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 meaning. All other computational linguistics tools degrade in performance when the data set is noisy or semantic understanding is insufficient. Examining context instead of semantics removes obfuscation created by "noise" in the oral and written communication, and scales up to deal with very large corpora.

LSA has been applied to a wide range of problems: full-text information retrieval (Foltz et al. 1998); assessing learning (Landauer et al. 2000; Shapiro and McNamara 2000); analysing the cognitive processes underlying communication (Landauer 1999); and assessing the outcome of design teams (Dong 2004). The problem, though, is the direct application of the LSA method to analysing text from a conversation. If one were to attempt to examine the coherence of a discussion over time based on the methods described by Song (2003) or Hill (2002), one would not obtain much useful information because of the high variation in context between one utterance and the next. If we were to assume, instead, that the topical focus of a design conversation should be coherent, then there should exist a mostly orderly relationship between semantic similarity and distance between utterance boundaries. An utterance boundary is defined by the turn-taking between speakers, that is, when one speaker stops talking and the next speaker begins. This orderly mapping can be revealed by looking at the coherence between any two utterances (communicative acts) as a function of the "distance" between the utterance boundaries. That is, instead of computing and plotting the coherence between adjacent utterances as suggested by Song (2003), compute the average coherence between utterances which are "one" utterance away, the average coherence between utterances which are "two" utterance boundaries away, and so forth, to expose the structuring of language over the entire conversation.

2.2. LSA FOR ANALYSING DESIGN TEAM DISCUSSIONS

The basic method for analysing text with LSA follows established procedures. We refer the reader to the cited sources above for detailed discussions on applying LSA. First, the utterances from the design team's conversation are entered into a database, recording an utterance identifier, the name of the speaker, and the utterance itself. The utterances may consist of multiple complete "sentences" or incomplete thoughts such as single word statements within an utterance boundary. Then, the utterances are parsed into principal phrases. Next, a term frequency matrix is constructed. The term frequency matrix counts the occurrences of the principal phrases in each utterance boundary. This term frequency matrix **X** is of dimension n (rows) words $w_1, w_2, \ldots, w_n$ and m (columns) utterance boundaries $d_1, d_2, \ldots d_m$ where each matrix entry indicates the total frequency of occurrence of term w_n in utterance d_m and $m < n$.

Then, the singular value decomposition (SVD) of the matrix **X** is computed. The SVD of **X** is defined as $\mathbf{X} = \mathbf{USV}^T$ where **U** (n x m) and **V** (m x m) are the left and right singular matrices (orthonormal), respectively, and **S** (m x m) is the diagonal matrix of singular values. SVD yields a simple strategy to obtain an optimal approximation for **X** using smaller matrices. If the singular values in **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 $\widetilde{X}$, which is approximately equal to **X** in the least squares sense, and is of the same rank. That is, $\widetilde{X} \approx \mathbf{X} = \mathbf{USV}^T$. The number of singular dimensions to retain is an open issue in the latent semantic analysis literature. Based on prior research (Hill et al. 2002), retaining the first 100 dimensions or dimensions 2 to 101 resulted in satisfactory performance. In this study, we retained the first 100 dimensions. We refer the reader to the literature (Deerwester et al. 1990) for the proof that the rows of the matrix VS are coordinates of the utterance in this k-reduced space. These utterance coordinate row-vectors form the basis for the coherence analyses. The final step is to compute the coherence of the utterances.

2.3. MEASURING THE COHERENCE OF UTTERANCES

The standard definition of the (cosine) coherence between any two adjacent utterances represented by the LSA vectors $\mathbf{d}_m$ and $\mathbf{d}_{m+1}$ is the dot product of the utterance vectors normalized by the product of their norm.

$$\chi_m^{m+1} = \frac{d_m \cdot d_{m+1}}{\|d_m\|\|d_{m+1}\|} \tag{1}$$

The ultimate objective is to consider how the topical focus (coherence) of a conversation changes during a design session. In the design sessions studied, each team’s conversation was goal-directed; the teams had to complete the design of an artefact that satisfied a prescribed set of goals and constraints. To examine the change in focus, the average coherence between utterances which are “one” utterance away, the average coherence between utterances which are “two” utterance boundaries away, and so forth, were computed and plotted.

3. Experimentation

3.1. DATA SETS

Two data sources were examined in this study. The first was a transcript from the mountain bike backpack design problem at the 1994 Delft Protocols Workshop with human analysis using the reflective practice as an observation method (Valkenburg and Dorst 1998). The transcript contains 2190 “raw” utterances among three design students over a 118 minute period. The second set comes from the Bamberg Study (Stempfle and Badke-Schaub 2002) of design thinking in teams based on their communication. There are three teams in the Bamberg Study, denoted by 1102, 2202 and 2302. Because the Java natural language parser (Stanford 2004) used for this research only parses English, the Bamberg transcripts were translated from German to English by native-language speakers with technical language proficiency and edited by the author for consistency in terminology by the two translators.

3.2. RESULTS

Figure 1 to Figure 4 display the average coherence between utterances as a function of distance between utterance boundaries for all transcripts. In the plots, the “distance” is the number of utterance boundaries between two utterances. The solid dots are the raw data; the open circles are a curve fit of the data (discussed below). The plots are intriguing in that they appear fairly regular with a non-zero slope initially, but approach an asymptotic limit. Outside a certain distance between utterances, the coherence ‘drops off’ and is highly scattered.

Dissecting the conversations by speaker, we can then look at the coherence of each speaker’s utterances, as in Figure 5 and Figure 6. The solid dots are the group’s utterance coherence (as before) and the other dots represent each speaker. For the Delft Protocol Study Team, (Figure 5), even though each speaker’s coherence is roughly constant, in additive, they increase the coherence of the conversation. It is as if the contribution of each person to the group’s conversation led to a more coherent conversation by the group; this appears to confirm the prior assessment of this team by the protocol analysts of the establishment of a shared understanding. Bamberg Team 2302 exhibited a similar conversation pattern as shown in Figure 7.

The Bamberg 1102 and 2202 Teams differed. Illustrating the per-speaker coherence for the Bamberg 1102 Team in Figure 6, one notes that each individual’s coherence is “scattered” within a band which also contains the group’s overall coherence, as shown by the solid red dots. That is, the contribution of each group member to the group’s discussion does not increase the coherence of the overall conversation.

The smoothness of the curves of Figure 1 to Figure 4 motivated the interest to investigate the regularity in the data set. Polynomial curve fits on the data were conducted to obtain the best polynomial curve fit in the least sum square of errors sense. The curve fit would offer a functional relationship between number of utterances and the coherence of those utterances from which metrics of coherent discussions could be derived. It was found that a 3rd degree polynomial curve (Eq. 2) best fit the data.

$$y = m_1x^3 + m_2x^2 + m_3x + m_4 \tag{2}$$

Using these curve fits, it then becomes possible to quantify coherent discussions via analytic metrics. Two methods are proposed: the loss of information and the rate of decay of coherence.

The first metric is based on the notion of measuring the loss of coherence using a decibel scale. The decibel scale is a convenient way to compare amplitudes. In this case, the amplitudes are the level of coherence of the discussions. The equation for the decibel scale is shown in Eq. 3 where c_0 is the average coherence for adjacent utterances and c is the coherence of an

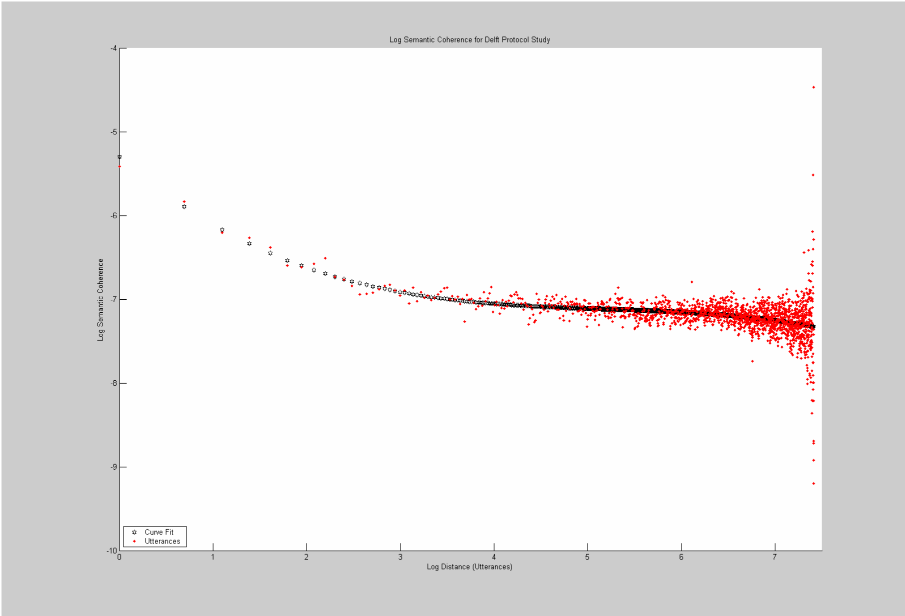

Figure 1. Log Coherence for Delft Protocol Team

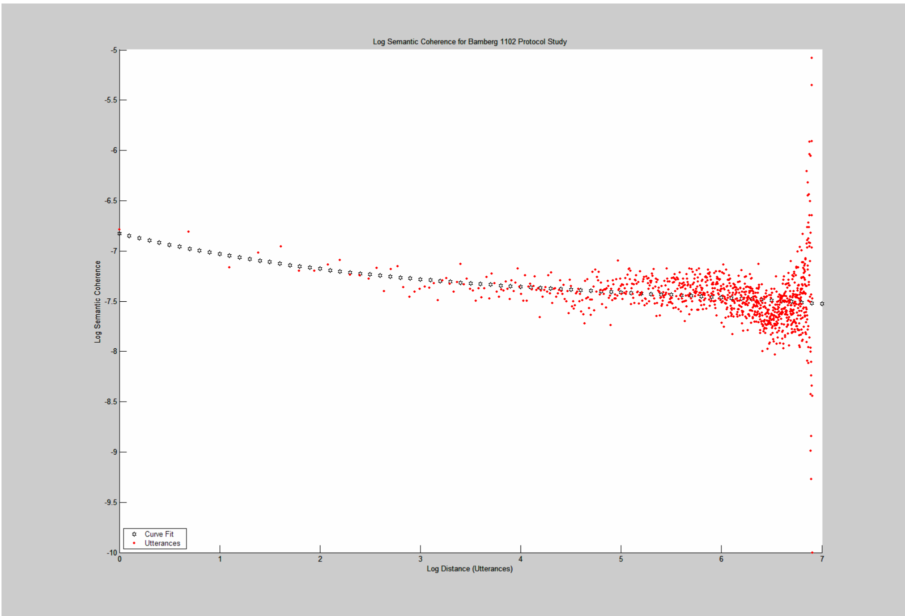

Figure 2. Log Coherence for Bamberg 1102 Team

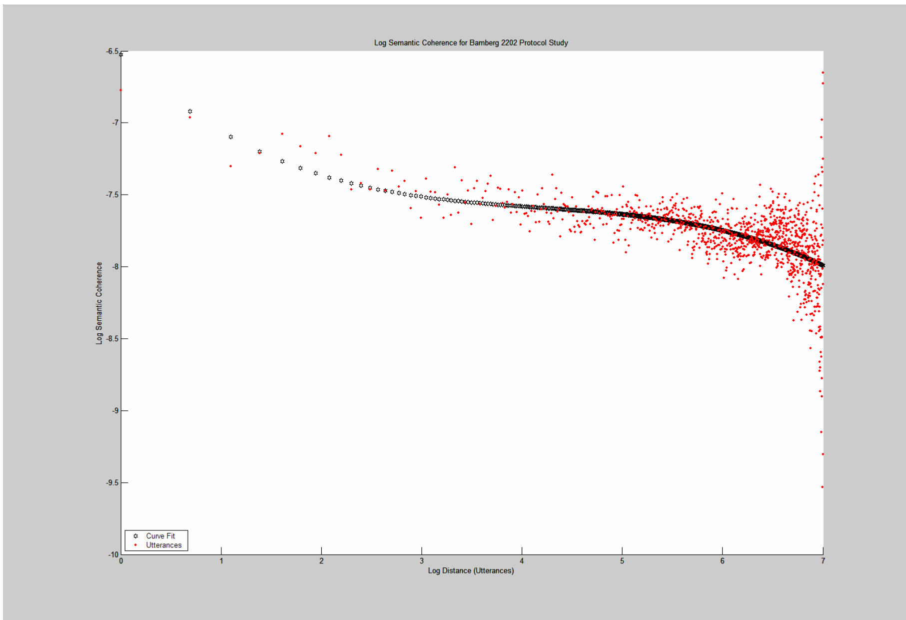

Figure 3. Log Coherence for Bamberg 2202 Team

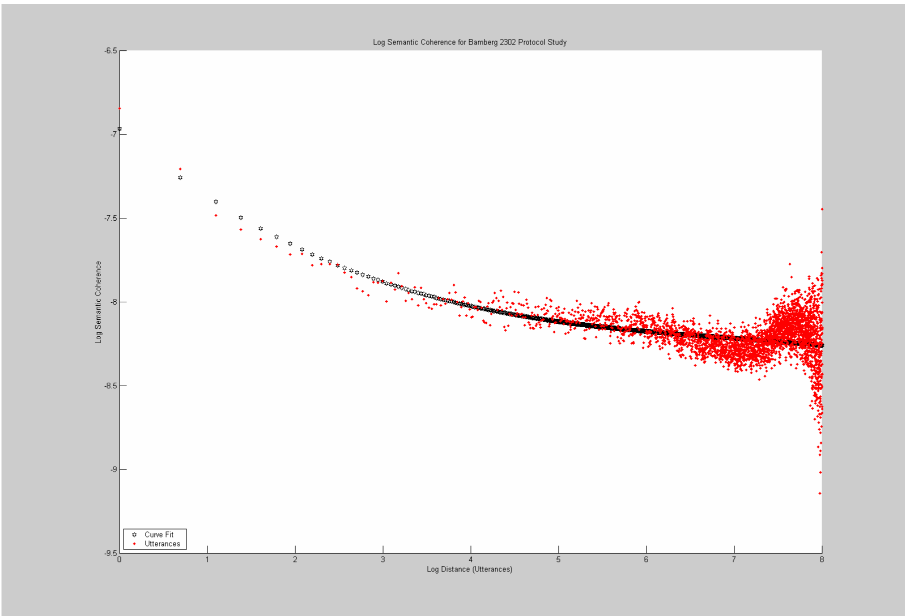

Figure 4. Log Coherence for Bamberg 2302 Team

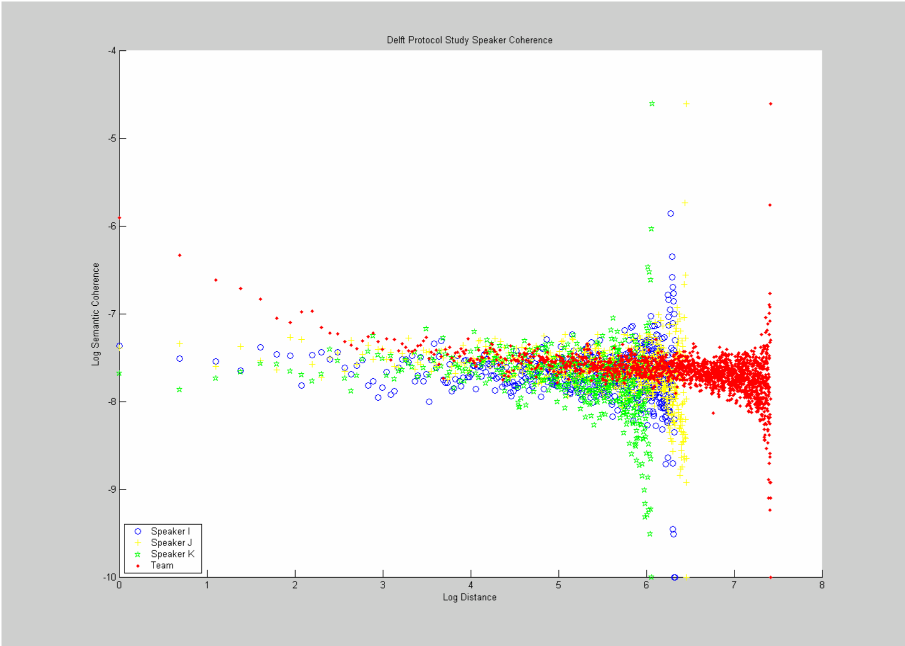

Figure 5. Delft Per Speaker Coherence

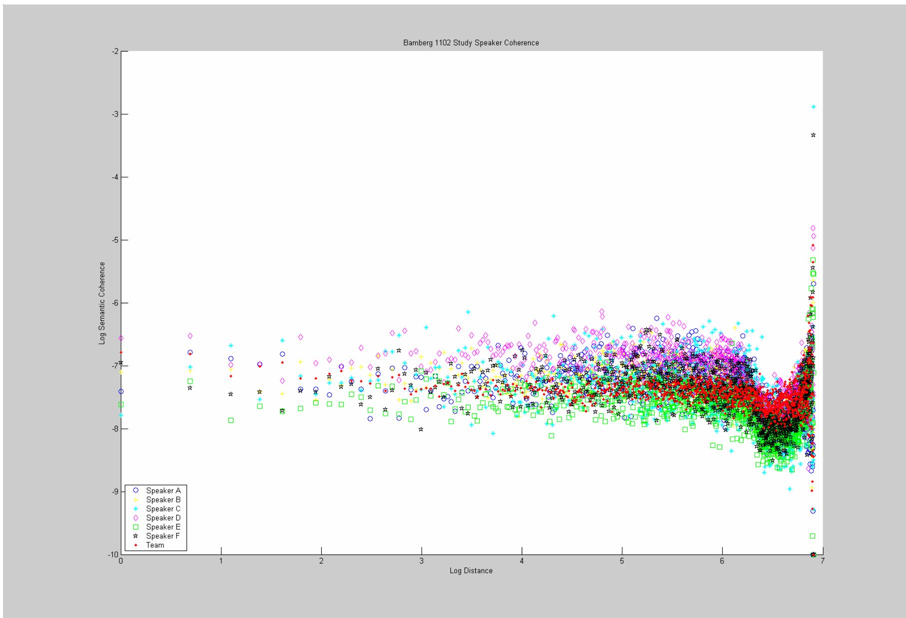

Figure 6. Bamberg 1102 Per Speaker Coherence

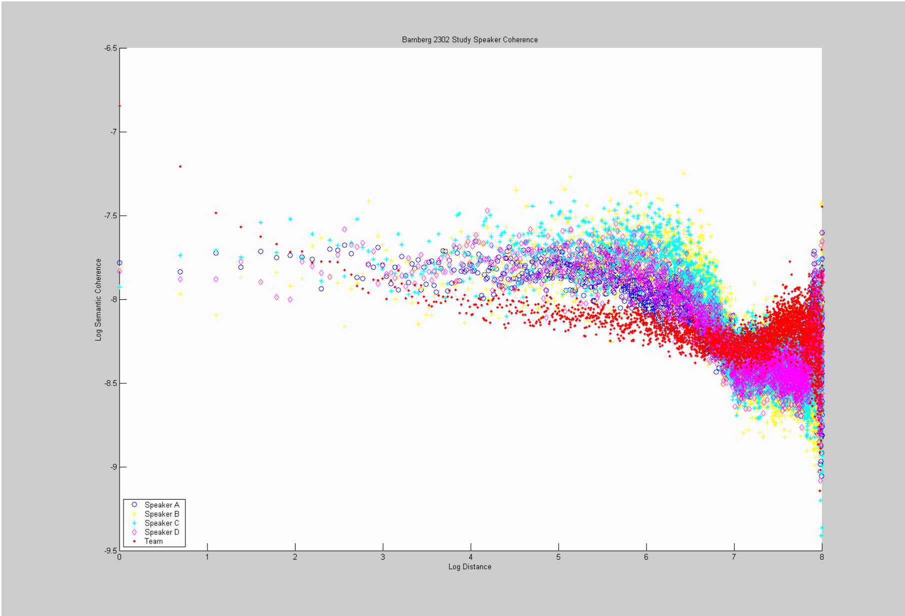

Figure 7. Bamberg 2302 Per Speaker Coherence

utterance an arbitrary number of utterance boundaries away. It is possible to solve for the decibel value c for a particular dB loss z and the corresponding value of x, the distance between utterances, by solving for the non-zero, real roots of Eq. 4.

$$20\log\left(c/c_0\right) = 1dB \tag{3}$$

$$\frac{m_1x^3 + m_2x^2 + m_3x + m_4}{m_4} - \exp\left(z/20\right) \tag{4}$$

The window size for utterance coherence for a given loss of coherence in a decibel scale is shown in Table 1 and Table 2 for the Delft Team and Bamberg Teams, respectively. The “All” indicates that all utterances would be considered within the window of coherence. To read the table, one would say, for example, that Bamberg Team 1102 loses 1 dB of coherence within 7 utterances and only 2dB throughout the entire conversation.

The second metric is based on the notion that the topic of the discussion will likely shift during a session. How quickly might the topic change? If the topics change quickly, an utterance is very likely to be less coherent with utterances that are physically “distant” (in time). Mathematically, we wish to find the slope of the best linear fit of the data within the incline region of the "raw" coherence data as in Figure 1. To do this, a linear curve fit was conducted from the first data point of the coherence data plotted as in Figure 1, which corresponds to the average coherence of adjacent utterances, to the point on the 3rd order curve fit where the first derivative is closest to 0. This point is defined as the asymptotic limit. The rate of decay of coherence of utterances is shown in Table 3 for the Delft and Bamberg Teams. To read these tables, one would say the Delft Team loses topical similarity at a rate of 19%.

TABLE 1. Delft dB Coherence

dB	Utterances
1	1.3
2	1.9
3	3
5	13

TABLE 2. Bamberg dB Coherence

dB	Utterances (Team 1102)	Utterances (Team 2202)	Utterances (Team 2302)
1	7	2	2
2	All	4	8
3	All	57	111
5	All	All	All

TABLE 3. Decay of Coherence

Team	Utterances
Delft	-19%
Bamberg 1102	-6%
Bamberg 2202	-17%
Bamberg 2302	-10%

The rate of decay of the Bamberg 1102 Team is 66% less than the Bamberg 2302 and almost three times lower than the Bamberg 2202 Team.

4. Discussion

4.1. DISCUSSION OF EXPERIMENTAL RESULTS

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 as exhibited by the Delft Team and Bamberg Team 2302, which we'll term *constructive dialog*, and one in which there was little in the way of building upon each other's expressions of ideas as demonstrated by the Bamberg 1102 and 2202 teams, which we'll term *neutral dialog*. The data sets examined do not reveal a third possibility, *destructive dialog*, in which each other's expressions of ideas negate one another.

Theories of socio-linguistics offer many explanations, as evidenced by the wide body of empirical literature that focuses on when and whether people adapt their discourse to each other, why these design teams might exhibit one of these three types of dialog patterns. Early on, Bahktin (Wertsch 1991) theorised that effective group communication occurs when the group shares a voice. The collective voice is dynamic; nevertheless, effective group communication occurs when all members are able to borrow from and relate to this combined group voice. The constructive dialog pattern supports this assertion. Conversely, when speakers lack "grounding," they may not initiate the next relevant contribution to the conversation (Clark and Schaefer 1987). The neutral and destructive dialog patterns offer empirical evidence of this situation.

From the design research standpoint, the challenge is not necessarily to understand the socio-linguistic factors that affect discourse, though those are important. What is of interest here is what the patterns of conversations imply about coherent thinking in the design team. If the objective of designers' conversations is to pool their resources to negotiate different design perspectives and specialties to solve a design problem, then the greater challenge is to infer what the empirical data depict about designers' individual and distributed mental processes while they are simultaneously involved in the collective activity of conversation and designing (which would involve drawing on paper or making simple models from available workspace materials.)

These three types of conversational coherence patterns revealed by the computational analysis could be related to behaviour associated with coherent thinking in design teams:

Constructive Dialog: By direct application of experience and each designer's knowledge to solve the design problem, indirect relations among components of knowledge stored in each designer's mind augment and expressed through conversation amplify coherent thinking by the group.

Neutral Dialog: While each individual designer may have a coherent plan "in mind" for solving the design problem, there is little attempt to reconcile each designer's "object world." (Bucciarelli 1994) The designers do not contribute to the conversation based on what has taken place before (i.e., what a previous designer has said/expressed).

Destructive Dialog: The design team is unable to reconcile viewpoints; the conversation breaks down due to disagreements. Collaboration and design suffer; thinking is incoherent.

For the DelftTeam, a move occurred on average every 28 utterances which, according to the computational data, is about 5½dB of loss of coherence. According to the Bamberg study, the teams "spend 8.3 communicative acts on content-related communication before switching to process-related communication" (Stempfle and Badke-Schaub 2002, p. 486). The switching could be thought of as changing the content of communication, or thinking coherently about the "content" and then about the "process." The value of 8.3 is a bit over 1dB loss of coherence for Team 1102, almost 2.5dB loss of coherence for Team 2202, and about 2dB loss of coherence for Team 2302. At this time, there is insufficient data or theory to make statements about the correlation between the computational metrics of coherent discourse and the moves and communicative acts that were ascertained by the protocol analysts. However other insights are available. Looking across the rows of Table 2, there is only a loss of 2dB for Team 1102 throughout their entire conversation whereas both Team 2202 and 2302 lose 5dB. The researchers reported that "proceeding in the design task can be labelled from "chaotic" (group 3) to "planned" (group 1)" (Stempfle and Badke-Schaub 2002, p.484). Yet, the above graphs showed that "group 3" (2302) exhibited a constructive dialog pattern. This apparent contradiction might be explained by the researchers' observation (Stempfle 2004; Stempfle and Badke-Schaub 2002) that this team experienced disagreements and challenges of ideas which nonetheless lead to careful analyses and selection of a design idea. Even though there is some of loss of coherence throughout their (2302) conversation, on the whole, these designers built upon each other's ideas. Thus, the computational analyses suggest that it would be faulty to automatically dismiss a team's conversation as being incoherent (and their thinking incoherent) when topics change quickly or where there appears to be high levels of disagreement. Rather, if the argumentation style builds upon prior evidence, then the resulting complete dialog may be constructive.

Also, the rate of decay is not apparently directly linked with the type of design team dialog. Even though Bamberg Team 2302 had a much higher rate of decay than Bamberg Team 1102, Figure 7 shows the dialog of Bamberg Team to be constructive whereas Bamberg Team 1102 is neutral.

Likewise, although the Delft Team had the highest rate of decay, this team has been shown to exhibit communication and design strategies to increase the level of shared understanding of the team. Again, rapid changes on topic of dialog during a design discussion may not necessarily indicate an incoherent conversation. In summary, the empirical results demonstrate the need to consider both the analytic metrics and the patterns.

The analysis of the conversation of the coherence of design team conversations was more complex than originally expected. Unfortunately, it was not possible to "assign a number" to the level of coherence of the conversation and correlate that to successful outcomes as had been done for communication in text. What are revealed by this computational analysis are aggregate patterns of how individuals contributed to the group conversation. That is, the analysis transforms the communicative residue of teams into devices for quantifying and visualising the level and quality of communication interactions. The analysis also provided accounting metrics of the nature of group conversations. Given that ethno-methodological methods and discourse analysis are beyond the capacity of design teams, automatically deducing characteristics of their communication may lead to feedback mechanisms which support them in assessing the state of their design sessions and adjusting their behaviour as required.

4.2. LANGUAGE, COMMUNICATION AND HUMAN COGNITION

What interpretations about coherent cognition do the results on coherent discussions provide? To answer this question, we must consider the relation between language, communication and cognition.

The intersection of language and human cognition is regarded as a fundamental insight to human cognition. The field of sociolinguistics examines how language works to convey information and to connect individuals to cognitive systems. Researches in human developmental psychology and language development, such as Vygotsky's (1978) body of work on the social origins of language and thinking, Bahtkin's (1981) thesis on the development of shared discourse through the assimilation of others' voices, and Wertsch's (1991) socio-cultural framework for mediated action, situate language expression and human cognition within social contexts and connect theories of human cognition to the physical and social world. In all, language acquisition, whether individual or social, is regarded as a key factor for understanding mental functioning.

The study of distributed cognition in design concerns with the generation, transmission and evaluation of information and knowledge to create collective sense-making of the function, behavior, structure and meaning of a product. This is based on Hutchins's (1995) *distributed cognition approach* which promotes the need to look at individuals and the artefacts and tools they use and at the social organisation factors that influence cognition.

Finally, a predominant model of how knowledge is stored in memory asserts that certain types of knowledge are stored as semantic memory (Quillian 1968).

The premise of the article was that the psychological similarity between stored knowledge as semantic memory in each designer's mind is reflected in the semantic coherence between words in the way they co-occur in dialog and other language-based communication.

Therefore, whereas verbal communication portrays the cognitive processes of the designers and whereas certain types of design knowledge are stored as semantic memory and distributed throughout each designer, we can hypothesise that the contribution of individual knowledge to the formation of the group's knowledge manifests in group verbal communications.

Given this hypothesis, one conservative interpretation of the empirical data is that some groups are more able to engage in a constructive dialog. But these teams aren't just talking for the sake of talking. They're engaging in a conversation to design an artifact. They have a goal-oriented conversation. Thus, a more radical interpretation of the data is that the patterns of utterance coherence portray the overlap of their knowledge and how the knowledge of each individual designer contributes to the group knowledge. The metrics of loss and decay of coherence appear to indicate how quickly the teams change directions in thinking rather than not thinking coherently.

Cognitive coherence is an important issue in design cognition research. The coherence of the collective mental functioning facilitates the coordinated action that is required for successful team-based design. Of the basic cognitive processes in design (Stempfle and Badke-Schaub 2002), exploration, generation, selection and comparison, exploration and generation serve to widen a problem space whereas comparison and selection narrow a problem space. Changes in coherent thinking should mirror the changing episodes of design cognition. That is, exploration and generation occur during periods of decreasing coherence (divergent thinking) whereas selection and comparison occur during periods of static or generally increasing coherence (focus). If these episodes could be identified automatically, then it would provide an effective means by which to analyse the frequency, duration and activities during these cognitive episodes. Other research (Valkenburg 2000) has shown that during these episodes design teams create shared understanding and that the nature of the design activities in these episodes can assist (or detract from) the establishment of shared understanding in design. A high rate of decay of coherence or loss of coherence might be an issue if the design team needs to stay on topic; however, the high rate might be desirable if they need to explore a wide variety of design solutions. Thus, the significance of the metrics and of the patterns is based on the design situation.

5. Design Cognition Viewer

While it may be possible to scale-up tools and methodologies from linguistics, cognitive psychology and anthropology to study the inter-relationship between communication and cognition, it is not *a priori* obvious how this could be done for any authentic scale design problems. Computational systems for characterising and critically reflecting upon cognitive performance based on communication could resolve the scale-up issue. For this reason, a prototype design cognition viewer, as illustrated in Figure 8, has been developed in conjunction with this research. The design cognition viewer is part of the "Team Thinking" module of Team Agora, a computational system being developed by the author for supporting reflective and productive collaboration in teams by rendering awareness of the social mechanisms that come into play in team collaboration. The team thinking module supports two main functions: analysis of periods of coherent cognition and a cognitive actions analysis (to be reported in a future paper.)

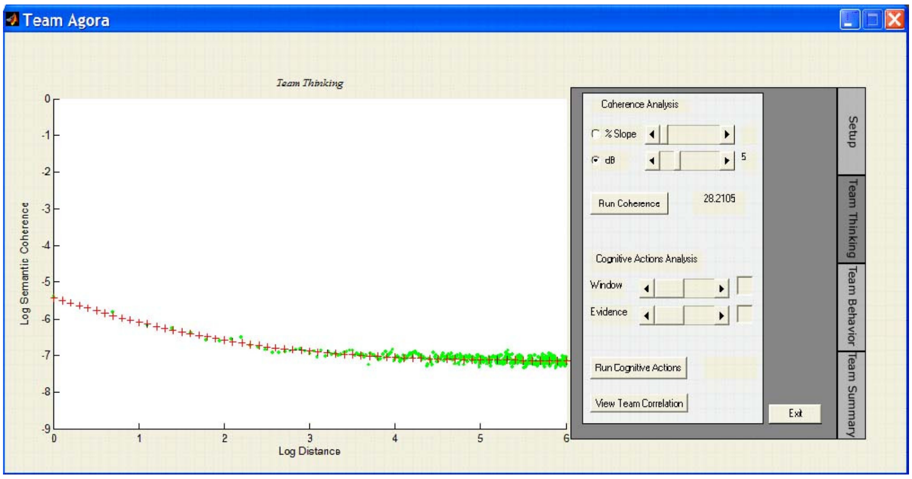

Figure 8. Design Cognition Viewer

As shown in the figure, the user can select the method (by dB or slope) by which to compute the duration of coherent thinking, displayed to the right of the "Run Coherence" button, by the team for a given data set. More importantly, though, the graph shows the rate of change and the variation in coherence. Recalling Figure 1 and Figure 2, there is a visible difference in the rate of decay of coherent conversation (thinking) between the Delft Team and the Bamberg Team 1102. While studies have not yet been conducted to ascertain whether this system actually encourages more reflective analysis of their thinking processes, it demonstrates an application of computational linguistic analysis for analysing design team conversations to make visually transparent team collaboration through communication in an accessible way to academics, researchers and people interested in reflection-upon-action of team processes.

Ideally, the viewer would be as rigorous and carefully constructed as “hand done” verbal protocol analysis. However, because the auto-generated visualisations of design cognition are faster to generate, one can utilise the results as a rough indicator or guide by which to segment verbal protocols to search for interesting areas. The design researcher can then conduct a more in-depth analysis of the dialog segments to ascertain boundaries between different cognitive episodes in design.

For the designer or the design teams, the design cognition viewer is intended to a means for reflection upon action by rendering transparent the history of their cognitive performance as demonstrated by their dialogs. Given the ethical issues associated with monitoring dialogs and the impression that such a tool subjects humans to microscopic surveillance, the intent is not to suggest realism in modeling cognitive performance but rather to encourage an atmosphere in which design teams continually self-monitor their performance to reflect upon action. Such a design tool is not a mechanical aid for improving the efficiency of specific design processes but rather intended to improve the effectiveness of the cognitive activities which take place during designing.

6. Concluding Remarks

The purpose of this paper was to address the methodological shortcoming of applying latent semantic analysis to the study of design communication in a conversation mode rather than in a text mode. As a practical method, LSA produces useful visual representations of the coherence of the discourse of design teams that enable design researchers to understand the nature of their conversation. Because LSA is nearly automatic, it permits the rapid analyses of a large number of design conversations in near real-time. This capability creates the potential to embed design assessment techniques into design environments and information and communication technology tools purported to *measurably* enhance the communication of design teams. There is much reported research that certain collaborative design environments support and improve communication in design teams and that “more” communication necessarily leads to improved team performance. A more objective assessment might be to measure whether the CSCW tools increase, decrease, or do not affect the ability of the design team to think coherently. Likewise, it would be interesting to study how computer-mediated interaction (such as in design collaboration environments) alters their conversations.

Computational methods such as the one described in this article make steps towards achieving the goal of including design cognition assessment techniques into computer-supported collaborative design environments. This type of analysis may lead to larger studies, in terms of the number of teams and the duration of the analysis of the teams' design period, of designers than is practical with protocol analysis. Clearly, not being able to quantify the influence of facial cues, gestures, and diagrams in the communication is a shortcoming. There exists nascent research on facial gesture recognition and computational shape emergence analyses which may lead to additional insights about the mental functioning of design teams.

In summary, a method for objectively measuring the cognitive coherence of design teams based on synchronous communication in a conversation mode has been presented. The impact of the research lays in the inclusion of these intelligent design cognition assessment techniques into design environments and information and communication technology tools intended to *measurably* increase the cognitive capacity of design teams. An interesting area of investigation would be to measure the effect of various media and computer-supported design and collaboration tools on the cognitive performance of design teams and the influence of such systems. One such question that could be addressed is *how much* digital communication environments alter the cognitive behaviour of design teams. Computational systems for characterizing and critically reflecting upon cognitive performance based on communication is part of continuing research in design cognition performance and management systems. The work contributes to an emerging research area on computational methods for studying the behaviour of designers.

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References

Bakhtin, MM: 1981, *The Dialogic Imagination: Four Essays by M.M. Bakhtin*, Holquist, M (ed), Holquist, M and Emerson, C (trans.), University of Texas Press, Austin, TX.

Bucciarelli, L: 1994, *Designing Engineers*, Cambridge, MA, MIT Press.

Clark, HH and Schaefer, EF: 1987, Collaborating on contributions to conversation, *Language and Cognitive Processes* **2:** 19-41

Deerwester, S, Dumais ST, Furnas, GW and Landauer, TK: 1990, Indexing by latent semantic analysis, *Journal of the American Society For Information Science* **41**(6): 391-407.

Ericsson, KA and Simon, HA: 1993, *Protocol Analysis: Verbal Reports as Data*, MIT Press, Cambridge, MA.

Dong, A, Hill, A and Agogino, A: 2004, A document analysis technique for characterizing design team performance, *Journal of Mechanical Design (to appear)*.

Foltz, PW, Kintsch, W and Landauer, TK: 1998, The measurement of textual coherence with latent semantic analysis, *Discourse Processes* **25**(2&3): 285-307.

Hill, A, Song, S, Dong, A and Agogino, AM: 2001, Identifying shared understanding in design using document analysis, *Proceedings of the 2001 ASME Design Engineering Technical Conferences*, Pittsburgh, PA, DETC2001/DTM-21713.

Hill, A, Dong, A and Agogino, AM: 2002, Towards computational tools for supporting the reflective team, *in* Gero, JS (ed), *Artificial Intelligence in Design '02*, Kluwer, Dordrecht, Netherlands, pp. 305-325.

Cross, N, Christiaans, H and Dorst, K: 1996, *Analysing Design Activity*, New York, Chichester.

Hutchins, E: 1995, *Cognition in the Wild*, MIT Press, Cambridge, MA.

Landauer, TK, Foltz, PW and Laham, D: 1998, Introduction to latent semantic analysis, *Discourse Processes* **25**: 259-284.

Landauer, TK, Laham, D and Foltz, PW: (2000, The intelligent essay assessor, *IEEE Intelligent Systems and Their Applications* **15**(5): 27-31.

Landuaer, TK: 1999, Latent semantic analysis: A theory of the psychology of language and mind, *Discourse Processes* **27**(3): 303-310.

Lawson, B: 1997, *How Designers Think*, Architectural Press, Oxford.

Mabogunje, A and Leifer, LJ: 1997, Noun phrases as surrogates for measuring early phases of the mechanical design process, *Proceedings of the 9th International Conference on Design Theory and Methodology*, Sacramento, CA.

Milne, A and Winograd, T: 2003, The iLoft project: A technologically advanced collaborative design workspace as research instrument, *Proceedings of the 13th Annual Intenational Conference on Engineering Design (ICED03)*, Stockholm, Sweden.

Quillian MR: 1968, Semantic Memory, *in* J Minsky (ed), *Semantic Information Processing*, Cambridge, MA, MIT Press.

Schön, DA: 1987, *Educating the Reflective Practitioner*, Jossey-Bass, San Francisco.

Shapiro, AM and McNamara, DS: 2000, The use of latent semantic analysis as a tool for the quantitative assessment of understanding and knowledge, *Journal of Educational Computing Research* **22**(1): 1-36.

Song, S, Dong, A and Agogino, AM: 2003, Time variation of "story telling" in engineering design teams, *in* A Folkeson, K Gralen, M Norell & U Sellgren (eds), *Research for Practice: Innovation in Products, Processes and Organisations*, *Proceedings of the 14th International Conference on Engineering Design*, Stockholm, Sweden, The Design Society.

Stanford JavaNLP Project. Retrieved from http://www-nlp.stanford.edu/javanlp/ on February 2, 2004.

Stempfle, J (js.beratung.training@gmx.de) (2004, 22 January), Group 3, E-mail to Andy Dong (adong@arch.usyd.edu.au).

Stempfle, J and Badke-Schaub, P: 2002, Thinking in design teams – an analysis of team communication. *Design Studies* **23**: 473-496.

Tang, JC and Leifer, LJ: 1998, A framework for understanding the workspace activities of designers, *Proceedings of the 1988 ACM Conference on Computer-Supported Cooperative Work*, ACM Press, New York pp. 244-249.

Valkenburg, R and Dorst, K: 1998, The reflective practice of design teams. *Design Studies* **19**: 249-271.

Vygotsky, LS: 1978, *Mind in Society,* Harvard University Press, Cambridge, MA.

Wertsch, J: 1991, *Voices of the Mind, A Sociocultural Approach to Mediated Action*, Harvard University Press, Cambridge, MA.