The Effects of Computer Tools upon Design Collaboration: A Case Study of Developing Methods to Study Design Collaboration

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Abstract: This paper aims to understand the effects and implications of introducing computer mediated collaboration tools in the design workplace through developing and applying quantitative methods to study design collaboration. This study examines the use of the FBS ontological coding scheme together with linkography as bases to analyze protocol studies. It demonstrates the potential of using it as a unifying quantitative approach to studying design protocols. Entropic measurement of linkographs provided another way to study a session and measure individual contributions quantitatively.

Key words: protocol analysis, design ontology, analysis method, design collaboration, entropy, linkography

Introduction

Designers increasingly work across geographically distant locations. With recent developments video conferencing, data and application sharing, and 3D virtual worlds give rise to opportunities for distance collaboration that never existed before. Previous studies show that the characteristic of team work/design is affected by a numerous of factors at different levels ranging from organizational and social context to the use of specific tools.[1-5] However there is insufficient understanding of how these tools affect the activities (both cognitive and workplace) of designers, especially, those design related activities.

In the past two decades, protocol analysis has become the defacto method for studying the cognitive processes of designers. Van Someran et al. (1004)[6] classified the procedures into five steps: conducting experiments, transcribing protocols, parsing segments, encoding according to a coding scheme, and interpreting the encoded protocols. However, there is no unified way of parsing segments nor a standard coding scheme, which makes different research studies of design collaboration incomparable. The motivation of this research is to develop unified quantitative tools for studing collaborative design activities. These included using an ontological appoarch[7, 8] to segment and code the data, linking these idea segments using linkography[9], measuring those linkographs with Shannon's entropy from information theory[10], and deriving design processes from coded linkographs.

1 The Experiments and Data

The experiments and data collection of this study contain three major phases and span over one year. The first phase is *in-situ* observations and documentations of the existing practices of architectural designers collaborating. Phase two contains pilot studies of engineers and architects simulating distance collaborating in different technological environments: 1) with the introduction of shared whiteboard, and 2) with the introduction of a 3D virtual environment.

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Phase three contains design experiments with five pairs of designers in three conditions: 1) collaborating face to face, 2) collaborating through a networked shared whiteboard, and 3) collaborating through a networked 3D virtual world. All the experiments were videotaped as were some of the in-situ design meetings. Maher et al (2006)[11] provided some basic information about the experimental setup and the network environments. In this exploration a portion of the data was selected to illustrate the methods under discussion. Of the 15 design sessions of phase three, the most creative face-to-face session, judged by the design outcome, was selected for examination with the proposed method. It was compared with their 3D virtual world session. The networked shared whiteboard session was not studied due its lack of distinction from the face-to-face session.

2 Theoretical Basis for Unify Quantitative Measurement Tools

2.1 FBS Ontology

The FBS ontology[7] models designing in terms of three classes of ontological variables: function, behaviour, and structure. In this view the goal of designing is to transform a set of functions into a set of design descriptions (D). The function (F) of a designed object is defined as its teleology; the behaviour (B) of that object is either derived (Bs) or expected (Be) from the structure, where structure (S) represents the components of an object and their relationships. A design description is never transformed directly from the function but undergoes a series of processes among the FBS variables. These processes include: formulation which transform functions into a set of expected behaviours; synthesis, where a structure is proposed to fulfil the expected behaviours; an analysis of the structure produces derived behaviour; an evaluation process acts between the expected behaviour and the behaviour derived from structure; documentation, which produces the design description. There are three types of reformulation: reformulation of structure, reformulation of expected behaviour, and reformulation of function. Reformulation of function is relatively rare, as it changes or redefines the design problem. Fig 1 shows the relationships among the eight transformation processes and the three basic classes of variables, which claim to be the fundamental processes for designing.

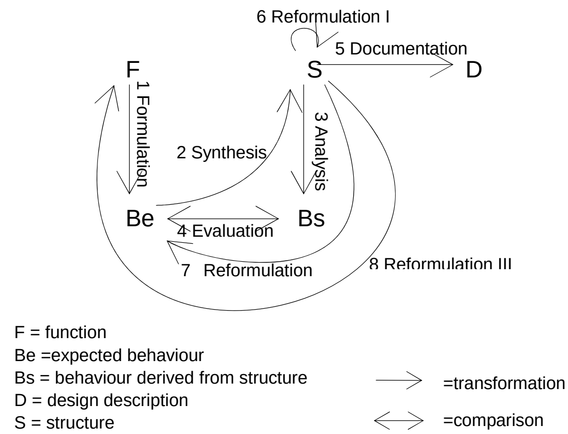

Fig. 1 The FBS Ontology

This framework was enhanced to include the idea of situatedness[12, 13] by introducing interactions of FBS variables among three worlds – the external, interpreted, and expected world. An agent or human interacts and understands the external world through their interpretation of the external world to form memories of his interpreted world. In order to change the external world (the act of designing) he needs focusing to transform memories to the expected world before taking actions in the external world. In this framework the original eight processes are expanded to twenty to account for all the processes as illustrated in Fig 2.

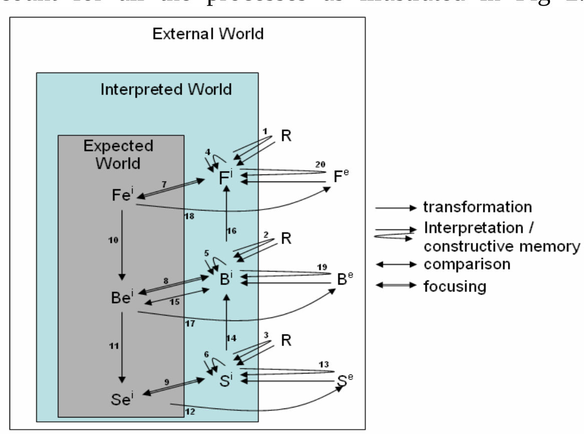

Fig. 2 The Situated FBS Ontology

The superscript "e" and "i" are used to represent variables are of external and internal world respectively; the suffix "e" is used to indicate the variable is of expected world. R represents the requirement which is being interpreted in terms of function (F^i), behaviour

(B^i), and structure (S^i). In the interpreted world there are four types of processes that the FBS variables can go through: transformation, comparison, reflection, re-interpretation, and focusing. Focusing refers to processes that produce an expected function (Fe^i) from an interpreted function (F^i), expected behaviour (Be^i) from interpreted behaviour (B^i), and expected structure (Se^i) from interpreted structure (S^i). Expected structure (Se^i) can also be transformed from expected behaviour (Be^i), which in turn can be transformed from expected function (Fe^i), which represents the synthesis and formulation process in the original FBS framework. The comparison is between expected behaviour (Be^i) and interpreted behaviour (B^i), which is similar to the evaluation in the original FBS framework. A design can be documented from expected world (Fe^i, Be^i, Se^i) in terms of function (F^e), behaviour (B^e) and structure (S^e). These external documentations (F^e, B^e, S^e) can be re/interpreted (F^i, B^i, S^i) during the design processes.

2.2 Ontological Coding and Linkograph

The design protocols were segmented according to the situated FBS ontology. Linkography is a technique used in protocol analysis to study the structure of reasoning of designers[9]. It was used to measure productivity of designers[14], study creative process[15], and examine the goodness of ideas[16]. A linkograph is constructed by linking related segments; links are established by discerning, using common sense, whether a move is connected to the previous moves. Fig 3 shows an extracted coded protocol together with the corresponding linkograph.

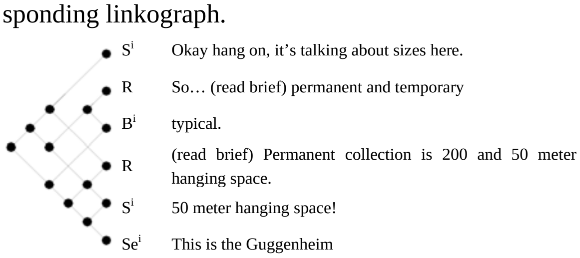

Fig. 3 Example of linkograph in relation to protocol

2.2.1 Deriving Design Process from Links

If segment n is connected to segment $n + i$, it is universally represented by $n \dashrightarrow n + i$ without specifying the type of processes. For example the link from the second and third segment in Fig 3 is represented by $R \dashrightarrow B^i$, which is an interpretation of the requirement. By doing this all the links become design transformation processes.

2.2.2 Entropy Measure of Linkograph

Kan and Gero[17, 18] used Shannon's entropy [10] to quantify a linkograph on the basis that fully linked and empty linked linkographs represent substandard design processes. An empty linked linkograph represents neither development nor consolidation of ideas; a fully linked linkograph suggests fixation and no diversification of ideas. A good design process has a balance among of link, which can be represented by entropy. In Shannon's information theory, the amount of information carried by a message or symbol is based on the probability of its outcome. For a system with n symbols, the average information per symbol, entropy H, is derived by Shannon as formula (1), where p_i is the probability or the frequency of occurrences of symbol i.

$$H = -\sum_{i=1}^{n} p_i \log(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \qquad (1)$$

In a linkograph the *ON* and *OFF* symbols are used to represent whether two segments are linked or unlinked. Therefore the entropy of a linkograph is calculated by using formula (2) and applies it to each segment twice, one for forward linking and one for backward linking as illustrated in Fig 4.

$$H = -p(ON)\log(p(ON)) - p(OFF)\log(p(OFF)) \qquad (2)$$

H will be zero if $p(ON)$ equals 1 or $p(OFF)$ equals 1. H will have a highest value of 1 when $p(ON)$ equals $p(OFF)$ equals 0.5.

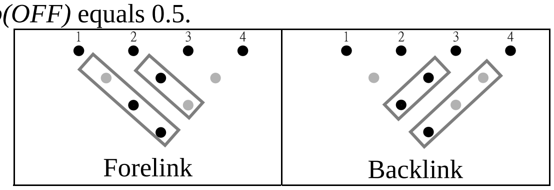

Fig. 4 Entropy measurement, black dots denote links.

Kan and Gero[18] suggested forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. If the idea in a segment is weak, it will not have a lot of forelinks ($p(OFF)$ is close to 1) and this produces a low entropy. However, if an idea gets too many forelinks ($p(ON)$ is close to 1), this might indicate fixation; which is also indicated by a low entropy. Similarly, if an idea is very novel, it will not have backlinks ($p(OFF)$ equals 1), the resulting entropy is zero. If an idea is linked backward to all previous ideas ($p(ON)$

equals 1), it lacks novelty and is represented by zero entropy.

3 Analysis of the Two Sessions

The team was asked to design a contemporary art gallery and a dance studio in the face-to-face condition and in the 3D world respectively. The same site was used and the complexities of the briefs were comparable. A1 and A2 are used to represent the two participants in this paper. In both sessions A1 seemed to take the leadership role and made decisions; he drew most of the sketches in the face-to-face session and organized most of the activities in the 3D virtual world session. In the face-to-face session the design process was closely coupled while in the 3D virtual world session the process was loosely coupled. In the 3D world session they tended to work more individually leading to the issue of the sense of presence. They used the webcam and avatars to detect each other. However, we found statements in the protocol like: "…you're not looking my way anyway", "the camera is not directed at you", and "I can't see you though…, I don't know where you are…" Also, they lost the ability to gesture. The design actions were through interaction with keyboard and mouse. In the face-to-face session they relied on gesturing to communicate, they gestured paths, shapes, and circulations. They also used gestures to signal drawing turn taking. The length of the verbal protocol in the face-to-face session was not only longer but also more concentrated on designing. There was more non-design activity in the 3D world protocol. Also, they developed more design ideas in the face-to-face setting than in the 3D virtual world settings.

3.1 Ontological Coding and Linkograph of the Two Sessions

The first 11 minutes of both sessions are examined here. There were 205 segments and 95% of them contained FBS codes in the face-to-face session. There were 125 segments in the 3D world sessions and 51% of them contained FBS codes. The low percentage in 3D world was a result of learning how to do things, especially in the beginning, like "how to fly", "how to get out", and "how to change colour". Actions of mouse and keyboard in the 3D world session were not segmented. So no external world actions were coded. However, there was a high percentage of structure which corresponded to the "design by making". Fig 4 compares the percentage of codes of the two sessions.

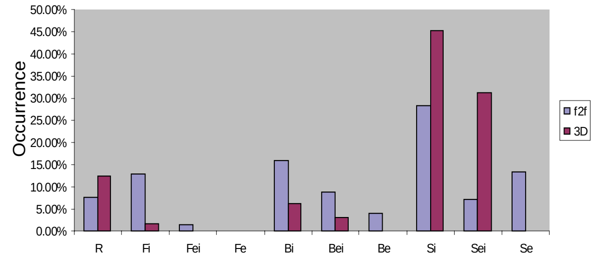

Fig. 5 Percentages of codes of the two sessions

There are 619 links in the face-to-face session and 92 links in the 3D-world session. 53 types of processes were recorded for the face-to-face session and 13 types for the 3D-world session. Some of these processes are meaningless because some segments do not have FBS codes, while others were the result of the granularity of segmenting. Kan and Gero (2007),[19] using a different set of data, gave some examples of how the granularity of segments affected the derived processes. In the 3D session many actions and activates were not captured because no verbalisation occurred while the designers were using the keyboard. These actions contain the manipulation of objects in the 3D-world.

The derived processes were grouped into the eight FBS categories. Fig 6 compares the percentages of the grouped processes. This shows and compares the distribution of processes but not the quantity of those processes. For example, the 79% of the type I reformulation process in the 3D-world session has 60 processes but the 38% in the face-to-face session has 225 processes. The distribution of synthesis, analysis and evaluation is similar to Maher et al's[11] propose, analyse solution and evaluation.

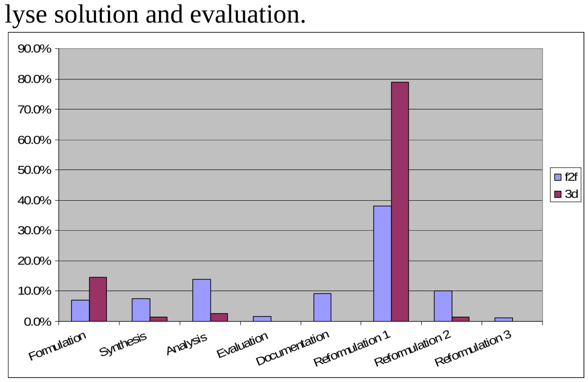

Fig. 6 Percentages of processes of the two sessions

3.2 Entropy Measure of the Two Sessions

Table 1 shows the entropy of the face-to-face and the 3D sessions. The face-to-face session had higher entropy than the 3D world session. In the face-to-face session the forelink entropy was higher than the backlink entropy which might indicate higher opportunity higher opportunity in initiating design ideas, which agreed with the qualitative analysis.

Table 1 Entropy of both sessions

	Face-to-face		3D World	
	Forelink	Backlink	Forelink	Backlink
Total H	47.48	42.18	11.64	15.53
H/Segment	0.232	0.206	0.105	0.140

Tables 2 and 3 show the forelinks and backlinks entropy contributions by individual participants. In both sessions A1 (the perceived leaders) contributed more segments and scored higher in both forelinks and most of the backlinks entropy in both sessions, except for the backlink per segment of the 3D world session.

Table 2 Individuals' entropy of the face-to-face session

Face-to-face	A1		A2	
	Forelink	Backlink	Forelink	Backlink
Segments	123		81	
Entropy	32.48	26.40	14.85	15.44
H/Segment	0.264	0.215	0.183	0.191

Table 3 Individuals' entropy of the 3D session

3D World	A1		A2	
	Forelink	Backlink	Forelink	Backlink
Segments	60		49	
Entropy	7.23	7.88	4.41	7.31
H/Segment	0.121	0.131	0.09	0.149

3.2.1 Deriving Design Process from Links

Kan and Gero[17] observed that the entropy varies across the time line. A 28-segment window was used to study the trend of entropy variations. The calculation starts from the first segment and advances to the next segment, until the window reaches the end. The changes of entropy across the design session can then be recorded. Those links outside the window are disregarded. Figs 6 and 7 record the entropy variation of the face-to-face session and the 3D world session respectively. In the legend, FH represents forelink entropy and BH represents backlink entropy. These show the contribution of individuals according to the goodness of ideas over a studies session.

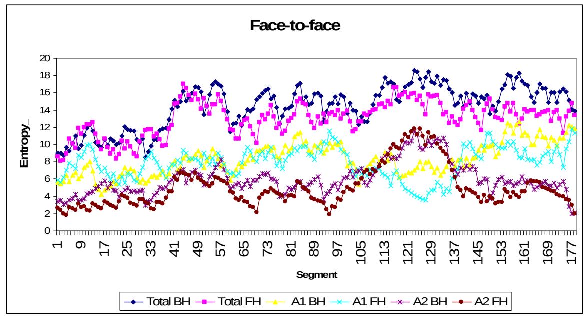

Fig. 6 Entropy variation of the face-to-face session

In the face-to-face session there was a clear cross over at around the segment number 105 where A2 started to contribute more good ideas and A1 started to take over around the 137 segment.

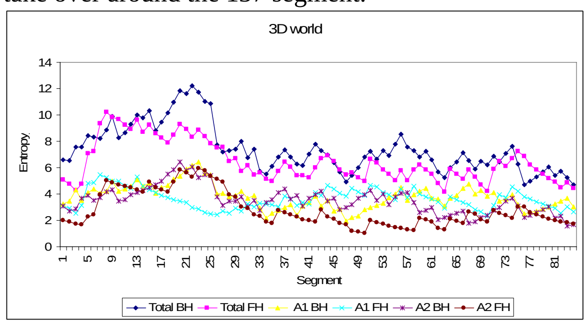

Fig. 7 Entropy variation of the 3D world session

4 Conclusions

Previous studies[20, 21] found that a particular entropy measure of a linkographs indicates the potential for design creativity and outcomes. Maher et al[11], using the same set of data but different analysis method, concluded that characteristics of the design process are quite different in sketching and 3D virtual environments. Our method of analysis shows comparable results in the domain of designing.

From the qualitative analysis we observed that the designers developed more design ideas in the face-to-face setting than in the 3D virtual world settings. This can be reflected in the entropy measures. The face-to-face session had much higher entropy per segment than the 3D world session. In the 3D virtual world the processes are very different; we observed that they worked more independently to create and make objects, and spent less time on generate and develop ideas. This was reflected in the derived processes, which had a high percentage of structure reformulations.

Many coding schemes, based on particular views of designing, have been developed for the analysis of design protocols. Usually, these schemes are unique to the data to which they are applied. This limits the applicability of the results obtained in that the results cannot be compared either across different codings for the same date or across different design sessions.. The FBS ontological coding provides a general framework to quantify a design session in terms of function, behaviour and structure. From the linkograph, ontological processes can then be derived. These provide a quantitative mean to compare design protocols.

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References

[1] Cross, N. and A.C. Cross, Observations of teamwork and social processes in design. *Design Studies*, 1995. **16**(2): 143-170.

[2] Gabriel, G.C., Computer Mediated Collaborative Design in Architecture: The Effects of Communication Channels in Collaborative Design Communication [i.e. Communication]. [Thesis]. University of Sydney, Sydney, 2000.

[3] Olson, G.M. and J.S. Olson, Distance matters. *Human -Computer Interaction*, 2000. **15**(2/3): 130-178.

[4] Oslon, G.M., et al., Small group design meetings: an analysis of collaboration. *Human -Computer Interaction*, 1992. **7**(4): 347-374.

[5] Zolin, R., et al., Interpersonal trust in cross-functional, geographically distributed work: a longitudinal study. *Information and Organization*, 2004. **14**(1): 1-26.

[6] Van-Someren, M.W., Y.F. Barnard, and J.A.C. Sandberg, The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes. Knowledge-Based Systems. 1994, San Diego, CA: Academic Press.

[7] Gero, J.S., Design prototypes: a knowledge representation schema for design. *AI Magazine*, 1990. **11**(4): 26-36.

[8] Gero, J.S. and U. Kannengiesser, The situated function-behaviour-structure. In: *Artificial Intelligence in Design '02*, J.S. Gero, Editor. Kluwer Academic Publishers, Dordrecht. 2002: 89-104.

[9] Goldschmidt, G., Criteria for design evaluation: a process-oriented paradigm. In: *Evaluating and Predicting Design Performance*, Y.E. Kalay, Editor. John Wiley & Son, Inc., New York. 1992: 67-79.

[10] Shannon, C.E., A mathematical theory of communication. *The Bell System Technical Journal*, 1948. **27**: 397-423.

[11] Maher, M.L., Z. Bilda, and L.F. Gul. Impact of collaborative virtual environments on design behaviour. In: Design Computing and Cognition'06. The Netherlands: Springer. 2006: 305-321.

[12] Clancey, W.J., Situated Cognition: On Human Knowledge and Computer Representations. Learning in doing: Social, cognitive, and computational perpectives, ed. J.S.B. Roy Pea. 1997, Cambridge: Cambridge University Press.

[13] Schon, D.A. and G. Wiggins, Kinds of seeing and their functions in designing. *Design Studies*, 1992. **13**(2): 135-156.

[14] Goldschmidt, G., The designer as a team of one. *Design Studies*, 1995. **16**(2): 189-209.

[15] Van-der-Lugt, R., Developing a graphic tool for creative problem solving in design groups. *Design Studies*, 2000. **21**(5): 505-522.

[16] Goldschmidt, G. and D. Tatsa, How good are good ideas? Correlates of design creativity. *Design Studies*, 2005. **26**(6): 593-611.

[17] Kan, J.W.T. and J.S. Gero. Entropy measurement of linkography in protocol studies of designing. In: Studying Designers'05: Key Centre of Design Computing and Cognition, University of Sydney. 2005: 229-245.

[18] Kan, J.W.T. and J.S. Gero, Acquiring information from linkography in protocol studies of designing. *Design Studies*, 2008. **to appear**.

[19] Kan, J.W.T. and J.S. Gero. Using the FBS ontology to capture semantic design information. In: DTRS'07. London: University of the Arts, London. 2007: 155-165.

[20] Kan, J.W.T. and J.S. Gero. Can an objective measurement of design protocols reflect the quality of a design outcome? In: ICED07. Ecole Centrale de Paris. 2007: 1-12.

[21] Kan, J.W.T., Z. Bilda, and J.S. Gero, Comparing entropy measures of idea links in design protocols. *AIEDAM*, 2007. **21**(4): 367-377.