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STUDYING DESIGNERS' BEHAVIOUR IN COLLABORATIVE VIRTUAL WORKSPACES USING QUANTITATIVE METHODS

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Abstract. This paper presents a case study comparing the behaviour of designers in a collaborative 3D virtual environment with those in a face-to-face environment using quantitative tools to examine their design protocols. It starts with depicting a design ontology along with two methods of analysis for this investigation. The results in this case show that the 3D environment increases the designer's Structure activities. The rate of meaningful design communication is slower than the base-line face-to-face session. This communication reflects the rate of design cognition when the design process is "close coupled". Reviewing the design protocol suggests that the 3D design session composed of both "loosely coupled" and "close coupled" periods. This is consistent with other studies that 3D collaborative tools may encourage "loosely coupled" design process.

Keywords. Design behaviour; virtual workspaces; protocol analysis; quantitative methods; design ontology.

1. Introduction

The concepts and technologies of using collaborative virtual environments have aroused researchers' and designers' interest since the nineties (Wojtowicz, 1995). However, virtual collaborative design environments, especially

3D environments, remain mainly in the academic research and teaching arena. They are not as popular as social virtual environments. We suspect this is due partially to the intention of those environments but also there is a lack of relevant tools to support design activities. On the other hand, our understanding of how tools impact design activities is limited. Over the past three decades, protocol analysis has become one of the most widely used methods to study human design activities and cognitive design processes (Christiaans and Dorst, 1996; McDonnell and Lloyd, 2007). Protocol analysis has also been used as a tool to study human behaviour in virtual environments (Maher et al., 2006). However, there is a lack of uniformity in both the method and coding of protocols when studying design activities and hence it is not possible to compare the results of the various studies. This paper explores the designers' behaviour by comparing two sets of protocol data – a 3D virtual world design session and a face-to-face design session – using generic methods and a generic coding scheme based on the FBS design ontology.

1.1. FBS ONTOLOGY AND GENERIC ONTOLOGICAL CODING SCHEME

The FBS ontology (Gero, 1990) models designing in terms of three classes of 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. The function (F) of a designed object is defined as its teleology; the behaviour (B) of that object is either expected or derived from the structure (S) which is the components of an object and their relationships. A design description cannot be transformed directly from the functions, which undergo a series of processes among the FBS variables. Figure 1 shows the relationships among those processes and variables. The eight processes: 1) formulation, 2) synthesis, 3) analysis, 4) evaluation, 5) documentation and 6–8) three types of reformulations, are claimed to be the foundation of all design processes.

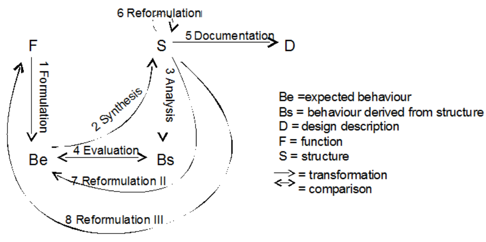

Figure 1. The FBS ontology of designing.

The generic coding scheme consists only of the function (F), expected behaviour (Be), behaviour derived from structure (Bs), structure (S), documentation (D) and requirement (R) code categories. The protocols are segmented strictly according to these six categories. Those protocols, utterances, which do not fall into these categories, will not be considered nor coded; these may include jokes, social communication, management, etc. Examples of these codings are given in figure 2 and table 1 in section 4. These fundamental FBS classes denote the state of affairs of designing of each coded segments. We anticipate this will capture the essence of design activities. Unlike many other complex coding schemes, this simple ontological coding scheme provides the foundation for further analysis. The eight design processes will be investigated using Markov analysis (Kan and Gero, 2009) and linkography (Kan, 2008) as outlined in the following subsections.

1.2. TRANSFORMATION PROCESSES: DERIVED FROM MARKOV CHAINS

Markov chains examine the sequence of events; they analyse or describe the probability of one event leading to another. A Markov chain is a discrete-time stochastic process with a number of states such that the next state solely depends on the present state. In the protocol analysis of design activities, McNeill et al. (1998) treated analysis, synthesis and evaluation as Markov states. They found that the most likely event to follow analysis is a synthesis event. Also the most likely event after synthesis is an evaluation event but the most likely event after an evaluation event is a synthesis event. In this paper, each coded segment is considered as an event of a Markov state. A 6 × 6 (the six code categories) transition matrix is used to describe the FBS Markov chain, as in (1), with which each row summing to one. P_{ij} is the probability of one state leading to another. For example P_{FBe} is the probability of having a Be event after an F event. This transition is likely to be a formulation process.

$$P = \begin{matrix} P_{RR} & P_{RF} & P_{RBe} & P_{RBs} & P_{RS} & P_{RD} \\ P_{FR} & P_{FF} & P_{FBe} & P_{FBs} & P_{FS} & P_{FD} \\ P_{BeR} & P_{BeF} & P_{BeBe} & P_{BeBs} & P_{BeS} & P_{BeD} \\ P_{BsR} & P_{BsF} & P_{BsBe} & P_{BsBs} & P_{BsS} & P_{BsD} \\ P_{SR} & P_{SF} & P_{SBe} & P_{SBs} & P_{SS} & P_{SD} \\ \multicolumn{2}{c}{\text{[redacted]}} & P_{DBe} & P_{DBs} & P_{DS} & P_{DD} \;\text{[redacted]} \end{matrix} \qquad (1)$$

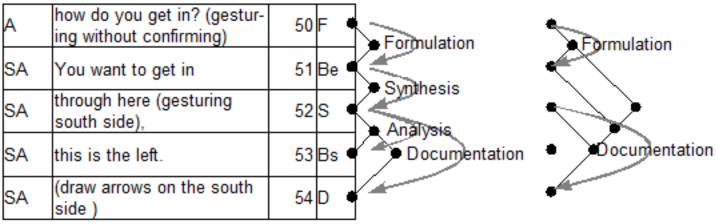

Figure 2. FBS processes derived from linkograph.
(a) Code protocol and human constructed linkograph; (b) WordNet generated.

1.3. TRANSFORMATION PROCESSES: DERIVED FROM LINKOGRAPHY

Linkography was first introduced to protocol analysis by Goldschmidt (1990) to assess the design productivity of designers. The design protocol is decomposed into small units called "design moves". A design move is "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt, 1995). A linkograph is then constructed by linking related moves, using common sense. The first order Markov analysis only considers the intermediate step but not the previous ideas. We expect by constructing a linkograph, connecting related segments, we will be able to capture the design processes in more detail. Figure 2(a) shows the annotated coded protocol together with its linkograph. The first column records the participants, A: the architect and SA: the senior architect. The second column contains the verbal protocol together with the annotations in brackets. The third column is the segment number and the fourth column contains the code. The dots represent the segments and the links and the grey arrow lines represent the derived FBS processes. The four links represent four FBS processes. Segment 52 has two links that indicate it spawns two processes: analysis (S to Bs) and documentation (S to D). This documentation process is not picked up by the Markov analysis.

Linkography has been criticised for the lack of objectivity in the construction of links, which is primarily based on the discernment and interpretation of the analysts. The process of constructing a linkograph is very time consuming and cognitively demanding, making it difficult and impractical to study and compare large data sets (Kan, 2008). Some analysts utilise the search function to help finding "moves" with similar semantic contents (Bilda, 2006). We propose to automate the construction of linkographs by connecting "moves" using an English lexical database, WordNet (Fellbaum, 1998). WordNet uses the concept of cognitive synonym to group words into sets. A program was written to connect the segments with similar meaning. Figure 2(b) shows the four connections that WordNet finds, only two of them matched the human constructed one. Not withstanding the differences, it picks up the "documentation" process that Markov analysis leaves out. We explore the WordNet generated linkographs and use it to complement the Markov analysis of the two sessions.

2. Virtual workspace benchmark against face-to-face design sessions

Two in-vitro architectural design sessions were conducted. The 3D session was benchmark against a face-to-face base line session. The participants remained the same in both sessions as did the complexity of the design task. Each session lasted for 30 minutes and was video recorded. The participants consist of a senior architect and an architect from the same company.

1. **Face-to-face design session.** In this experiment the designers were asked to design a university student union gallery. The senior architect took the leadership role, made most of the decisions, and did most of the sketches. This session can be divided into four stages or episodes, based on the design activities. In the first episode they dealt with the brief and site (about 3.5 minutes). In the second episode they analysed, planned and developed concepts in the plan (about 9 minutes); issues like location of main entrance and service entrance, icon to capture attention were discussed. In the third episode they developed the 3D form in elevation (about 9 minutes); ideas like "ribbon", "hole in the middle" were suggested. In the final episode they worked on the layout, calculated the required areas, in the plan until the end (about 8.5 minutes), but they did not finish it within the 30 minutes allocated

2. **3D virtual world design session.** A customised Active Worlds, an avatar-based multi-user virtual environment (http://awportals.com/), was used in this experiment, and both participants received prior training. The design task was to generate a conceptual design of a dance studio. The senior architect organised most of the activities. The stages were not as well defined as in the face-to-face session. This session can be characterised as "designing through making". Sometimes they subdivided the tasks and worked individually. They were given predefined elements – space, slab, wall, column, and beam – in various sizes. They decided to start with the biggest space element to represent the "largest" spaces, the four studios. At around 12 minutes, they discovered they could not have all the studios on one level because of the site coverage constraint. The senior architect decided to stack the blocks, the studios, and create an atrium to join them together. They tried to further develop this concept to accommodate the requirements but did not finish the design. Besides designing, time was spent on design support activities, such as discussing what elements were available and organising what to do. Also, time was spent on the technical aspects of learning how to do things, such as changing the colour of the blocks, how to "fly", and how get out when "trapped inside" those blocks.

Table 1. Example coding from the sessions.

Code	Face-to-face	3D Virtual Workspaces
R	(read brief) Permanent collection is 200 ...	They want four studio's mate, two one hundred each.
F	Hang on, that's a public building.	If it's a dance school it might still need a loading space.
Be	Can we say this is sort of external?	We need to, the obvious thing we've got... the generic space...
Bs	So these guys are coming across, they will be ...	that's very small area, court yard terrace and rough space ...
S	This is the Guggenheim	I don't know what size they are.
D	(draw arrows)	(insert box)
Not Coded	How long do we have?	"I can't see you though"

3. Coding and results

Table 1 shows examples of segments from the two design sessions in relation to the coding categories. In this exploratory case, the first sheet of drawing was studied. The coding was self-arbitrated with 90% agreement. In another study of over 1,000 segments, the inter-coder agreement with the arbitrated set was about 90% and the inter-coder agreement was about 80%. The biggest disagreement appeared in the Be and Bs codes. Out of the 205 segments in the face-to-face session, 192 of them contain FBS code.

The virtual world session contains 155 segments and 94 of them have FBS codes. Fig. 3 shows the frequency and the percentage distribution of the FBS codes, only consider those segments with FBS codes.

Chi-tests reveal that the FBS frequency distributions of the codes do not bear any relation. The segment per minute of the face-to-face and the virtual world sessions are 18.6 and 14.1 respectively. However, the FBS segment per minute of the face-to-face and the virtual world sessions are 17.5 and 8.5 respectively. This is a rough indication that the rate of design activities of the face-to-face session is two times faster than the 3D session.

Code	Face-to-face	3D
R	16 (8)	7 (5)
F	19 (9)	2 (1)
Be	32 (16)	5 (3)
Bs	25 (12)	7 (5)
S	65 (32)	53 (34)
D	35 (17)	20 (13)
Not Coded	13 (6)	61 (39)

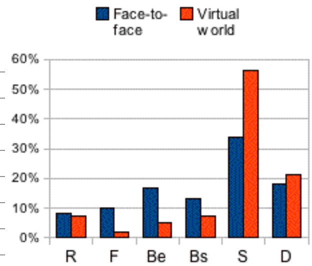

Figure 3. Frequencies and percentages (in brackets) distribution of FBS codes.

3.1. MARKOV TRANSITION OF THE SESSIONS

Equations (2) and (3) show the transition matrices of the two sessions.

P_{f2f} = (2)

	R	*F*	*Be*	*Bs*	*S*	*D*
R	0.00	0.00	0.40	0.00	0.40	0.20
F	0.00	0.18	0.45	0.00	0.27	0.09
Be	0.00	0.08	0.00	0.04	0.20	0.68
Bs	0.12	0.00	0.35	0.24	0.18	0.12
[redacted]	[redacted]	[redacted].04	0.15	0.10	0.46	0.23
[redacted]	[redacted]	[redacted].15	0.15	0.18	0.42	0.03

P_{3D} = (3)

	R	*F*	*Be*	*Bs*	*S*	*D*
R	0.14	0.00	0.00	0.43	0.43	0.00
F	0.00	0.00	1.00	0.00	0.00	0.00
Be	0.00	0.00	0.00	0.00	0.60	0.40
Bs	0.43	0.00	0.00	0.00	0.43	0.14
[redacted]	[redacted]	[redacted].02	0.02	0.06	0.60	0.27
[redacted]	[redacted]	[redacted].05	0.10	0.05	0.65	0.15

If we rank the probabilities, the highest is the F to Be in the 3D session that is 1.00. This mean whenever there is an F event a Be event will follow. This transition represents the formulation process, assuming most of the consecutive events were related. Both the Be to S and S to S are 0.60. The Be to S probability can be seen as the probability of a synthesis process when a Be event occurs. Similarity, the S to S transition probability can be seen as type 1 reformulation probability when an S event occurs. The type 2 reformulation is lower than type 1 reformulation in the two sessions. Type 3 reformulations are very rare. The probability of an analysis process from an S state (S to Bs) is surprisingly low in the 3D session. Figure 4 shows the probability of the eight FBS processes, as depicted in figure 1, triggered by the FBS events of the two sessions. For the evaluation process, we added the Bs to Be and Be to Bs transition probabilities. The distribution of the probabilities of the FBS processes of the two sessions look very different.

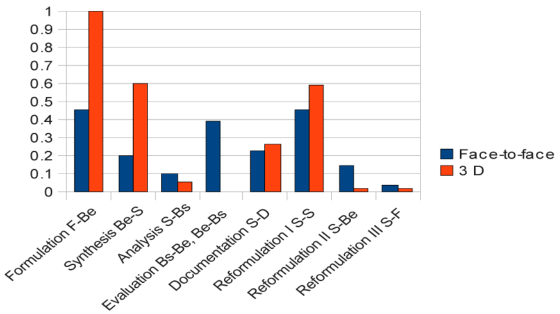

Figure 4. The probability of the FBS design processes triggered by events.

The mean first passage time is the average number of steps traversed before reaching one state from another state. The mean passage time can be obtained from the transition matrix (Kemeny and Snell, 1960). Equations (4) and (5) show the mean first passage matrices of the two sessions.

$$M_{f2f} = \begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ R & 49.96 & 16.85 & 5.38 & 10.86 & 3.24 & 4.07 \\ F & 50.32 & 14.23 & 4.86 & 11.19 & 3.74 & 4.39 \\ Be & 49.35 & 15.48 & 7.06 & 10.19 & 3.73 & 2.95 \\ Bs & 46.11 & 17.21 & 5.24 & 8.68 & 4.09 & 4.42 \\ \multicolumn{2}{c}{\text{[redacted]}} & 16.54 & 6.54 & 9.80 & 3.05 & 4.33 \\ & & 15.22 & 6.15 & 9.32 & 3.27 & 5.02 \end{array} \quad (4)$$

$$M_{3D} = \begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ R & 23.04 & 59.66 & 22.54 & 9.35 & 2.58 & 6.11 \\ F & 31.21 & 59.15 & 3.64 & 18.46 & 2.97 & 4.70 \\ Be & 30.21 & 58.15 & 20.85 & 17.46 & 1.97 & 3.70 \\ Bs & 20.42 & 59.33 & 22.16 & 14.37 & 2.51 & 5.52 \\ \multicolumn{2}{c}{\text{[redacted]}} & 57.65 & 20.58 & 16.26 & 2.05 & 4.37 \\ & & 56.40 & 18.75 & 16.76 & 1.96 & 4.75 \end{array} \quad (5)$$

The longest mean passage time is from R to F (59.66) in the 3D session and the shortest is from D to S (1.96) also in the virtual world session. The average mean passage time of the face-to-face session and the virtual world session are 14.72 and 21.06 respectively. The minimum of this average occurs when all the events are evenly distributed, that is the transition probabilities are all equal. The virtual world session is comparatively more disproportionate. It has a fast occurrence of structure (the column of S in (5)) and slow occurrence of function (the column of F in (5)). The face-to-face session has also a fast occurrence of structure but the slowest occurrence is requirement (the column of S and R in (4)).

3.2. TRANSFORMATION OF FBS LINKOGRAPHS OF THE SESSIONS

WordNet finds 4,261 and 2,929 links in the face-to-face and the virtual world sessions respectively and their corresponding average links per segment, also called link index, are 20.79 and 18.90. Table 2 shows the number of links

Table 2. Number and percentages (in brackets) of FBS processes derived from WordNet.

Links	**Face-to-face**	**3D**	**Links**	**Face-to-face**	**3D**
R-F	45 (2.37)	8 (1.11)	F-Be	65 (3.42)	2 (0.28)
Be-S	269 (14.16)	21 (2.92)	S-Bs	178 (9.37)	34 (4.73)
Be-Bs	79 (4.16)	1 (0.14)	Bs-Be	101 (5.32)	7 (0.97)
S-D	238 (12.53)	25 (3.48)	S-S	562 (29.58)	542(75.38)
S-Be	200 (10.53)	46 (6.40)	S-F	163 (8.58)	33 (4.59)
Others	2361	2210	Total	4261	2929

that are considered to be legitimate FBS processes. The 3D session has much higher non-legitimate FBS links and a much higher percentage of S to S links. Figure 5 groups those processes into the eight FBS processes. The virtual world session is not only predominantly biased towards *structure*-related activities, but 75.38 % are *structure*-to-*structure* activities. Evaluation activates are rare (1.11%) so are the formulation activates (1.39%). This maps well with our observation of "designing through making" as depicted in section 2. Comparatively, the face-to-face session has higher percentages of all the FBS processes except for the type I reformulation (S to S). The face-to-face also has a high percentage of *structure*-to-*structure* activities (29.58%), followed by synthesis (14.16%) and documentation (12.53%). Formulation has the lowest percentage (5.79%). The percentage of other processes ranges from 8.5% to 10.6%. The result is also consistence with our observations and qualitative analysis of the first and second episodes briefly mentioned in section 2.

4. Conclusions and discussions

The speed of meaningful communication exchange, number of FBS segments over time, is much higher in the face-to-face baseline session (17.5 against 8.5). This speed in some way reflects the rate of design cognition. The most possible explanation is that there is a cognitive resources overhead in using the virtual environment.

The Markov transitions provide an indication of the distributions of the eight FBS processes by assuming that high percentages of the consecutive segments indicate a direct relation. The distribution of the probabilities of the FBS processes of the two sessions looks very different. The probability of an analysis process and evaluation process are surprisingly low in the 3D session. The mean first passage time matrix shows that the *structure* is the dominant

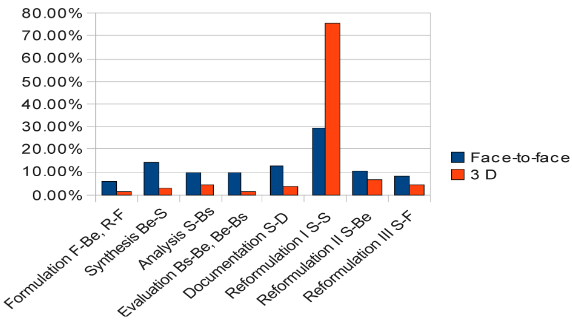

Figure 5. The percentage of the FBS design processes derived from WordNet.

state in the 3D session. The links and FBS processes derived from WordNet linkographs are consistent with the Markov analysis.

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