Generalizing Design Cognition Research

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Abstract

This paper presents an argument for the need to have commonly agreed methods of researching design cognition. It introduces an ontologically-based coding scheme capable of being used to determine issues and processes in a design session independent of the design task, the designer or the design situation. This will allow for comparisons of results from different researchers. The paper further argues that a set of standard analyses of the coded protocol is required to allow for the comparison of the results across researchers.

The FBS ontology is presented as one of a number of useful general coding scheme. A set of standard analyses is described that have the potential to produce results that inform the development of both general and detailed understandings of designing. These standard analyses can be turned into an open source computational tool that can perform the analyses in a standard manner and produce results in a portable form.

The paper concludes with examples of the kinds of results that can be obtained and the comparisons that can be obtained with generalized methods of coding protocols and using general analysis methods.

1. Motivation

The development of a scientific understanding of design requires empirical data from designers designing on which to found and test models of designing. One method of collection of that data is through the study of design cognition. Most models of design assume that designing is a process, rather than being some mysterious activity, and as a consequence design cognition can be studied scientifically. For a field to progress researchers must build on the work of others. Progress in design cognition research has been hampered by the inability of researchers to build on the work of other researchers. This has been caused by a lack of commonly used methods and commonly agreed analytical tools.

Whilst there are many ways of viewing designing the claim is made that the fundamental issues and processes involved in designing are not uniquely related to any particular design task, designer or design situation (Asimov 1962; Coyne et al 1990; Dieter and Schmidt 2008; Dixon 1996; Dym 1994; Eggert 2002; Eide et al 2001; Ertas et al 2008; Gero 1990; Gero 1991; Gero 2008; Hatamura 2006; Lawson 2005; Matthews 1998; Rychener 1988; Ullman 1992) and the issues and processes can be studied independently of the design being produced.

This is not to imply that there is only one way to carry out research into design cognition, rather it is suggested that within a research paradigm there is no commonly used approach to utilizing the source data and that without such an agreement it is difficult for one researcher to build directly on the results of another researcher and that this impedes progress.

Based on a survey carried out by the author there are four primary techniques currently available for studying designers: survey instruments; input-output experiments; protocol analyses; and fMRI-based cognitive neuroscience.

Surveys are not useful in cognitive studies as they are post-hoc and are unable to produce the level of granularity required. They are useful in other kinds of studies of design but not in cognitive studies (Murty and Purcell 2004). Input-output experiments treat the designer as a black box. Useful knowledge can be obtained using this technique but it does not produce any direct evidence for specific cognitive design behavior (Jansson and Smith 1991; Purcell et al 1996; Purcell and Gero 1996). Protocol analysis is a technique that converts verbal utterances to data that can then be studied. Cognitive neuroscience provides a physiological basis for cognitive activities. Currently, our knowledge of design cognition is insufficient for fMRI-based cognitive neuroscience to provide a useful foundation. Research is still at the exploratory stage in using this technique (Alexiou et al 2010).

Protocol analysis (Crutcher 1994; Ericsson and Simon 1993; Svenson 1974; Van-Someren et al 1994) is a tool that has been used to study design cognition. It has produced results across a variety of domains (Adams and Atman 1999; Cross et al 1992; Cross et al 1996; Eastman 1969; Ennis and Gyeszly 1991; Gero and McNeill 1998; Kavakli and Gero 2002; McNeill et al 1998). However, there has been a significant impediment with the application of protocol analysis in studying designing and this has been the lack of the means to compare the results of different analyses. This has been caused by the use of ad hoc coding schemes applied by different researchers even when tackling the same task. The use of ad hoc coding schemes has previously been recommended as a way of eliciting details from the domain (Ericsson and Simon 1993). This can be seen in the results published in Cross et al (1996), where different researchers carried out protocol analyses over the same data set. Each research group used their own coding scheme and as a consequence the results are not comparable. Eleven years later in September 2007 a similar exercise was carried out, where different research groups were given the same data set and were asked to analyse it. In the intervening 11 years between the first and second exercise the same problem was still exhibited, namely that each research group used its unique coding method in the protocol analysis, and again it was difficult if not impossible to compare results (McDonnell and Lloyd 2009).

Given the claim that the fundamental issues and processes involved in designing are not uniquely related to any particular design task, designer or design situation, it should be possible to produce general coding schemes for protocol studies that address fundamental issues and processes; a general coding scheme is one that can be used across design domains and design environments.

Designing is not a unitary activity and it is unlikely that a single coding scheme will be capable of capturing all its nuances. However, as in all science, the claim is made that there is a regularity in designing that transcends any individual and it is that regularity that is being studied. An ontology is one means to provide a framework for that regularity. Depending on the focus that is being taken a number of potential ontologies could be constructed, however, very few general ontologies have been produced for designing.

One such exemplary ontologically-based coding scheme has been proposed based on the Function-Behavior-Structure ontology of design (Gero 1990; Gero and Kannengiesser 2004). In this ontology the codes are the issues and the connections between the codes directly map onto design processes, as a result design processes are a consequence of the ontology rather than a separate part of the ontology. The claim for the use of this ontology is based on the widespread reference to it in the design literature. Scholar.google indicates that the two papers, which outline the ontology, have over 900 citations between them. A Monte Carlo simulation of 50 selections from these citations, excluding self-citations, shows the breadth of the disciplines the citations come from, Figure 1. This is not claimed to be the only coding scheme capable of capturing issues and processes, however, it is a scheme based on an existing ontology that is referenced one order more often than other coding schemes. It may be possible to map one ontology onto another but this is not explored here.

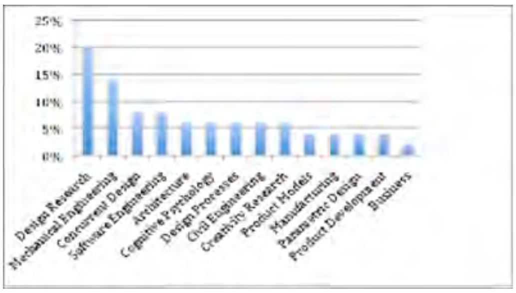


Figure 1 Distribution of disciplines citing the FBS papers (Scholar.google 2010)

In addition to a coding scheme that can be widely used, coded protocols need to be analyzed using either commonly agreed methods or methods that produce results that can be compared.

2. Protocol analysis

Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking (Crutcher 1994; Ericsson and Simon 1993; Van-Someren et al 1994). It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers (Adams and Atman 1999; Atman et al 1999; Atman and Bursic 1999; Badke-Schaub et al 2007; Christensen and Schunn 2007;

Cross et al 1996; Ennis and Gyeszly 1991; Gericke et al 2007; Gero and McNeill 1998; Goldschmidt 2003; Kavakli and Gero 2002; McDonnell and Lloyd 2007; McNeill et al 1998; Purcell and Gero 1998; Purcell et al 1996; Suwa and Tversky 1997; Suwa et al 1998; Suwa et al 2000; Tang and Gero 2002).

2.1 FBS coding scheme

The FBS coding scheme can be summarized, using the design terminology embodied in Figure 2, with the addition of the symbol R for Requirements. This produces six codes for issues, Table 1.

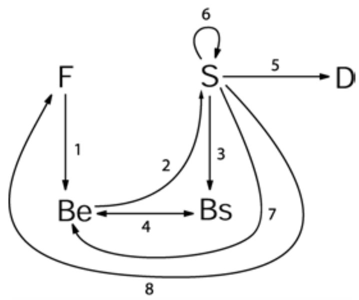


Figure 2 The FBS ontology, labels are issues, numbers are resulting processes

Table 1. FBS Codes

Code
R
F
Bs
Be
S
D

The processes are directly derivable from the protocol's linkograph. Linkography is a technique used in protocol analysis to study the structure of reasoning of designers (Goldschmidt 1990). It has been used to measure the productivity of designers (Goldschmidt 1995), study creative processes (Van-der-Lugt 2000), and examine the goodness of ideas (Goldschmidt and Tatsa 2005). Linkographs can be of two kinds. A syntactic linkograph is based on the assumption, which is a weak assumption, that adjacent segments are related to each other and are therefore linked. This produces a graph of depth 1. A semantic linkograph is based on the notion that only segments that have a semantic connection are linked. Since each end of a link has an issue associated with it, a link consequently defines a process. Table 2.

Table 2. Processes from FBS Codes, the numbers in rackets refer to the processes numbered in Figure 2

Design Process	
Formulation (1)	R>F,F>Be
Synthesis (2)	Be>S
Analysis (3)	S>Bs
Documentation (5)	S>D
Evaluation (4)	Be<>Bs
Reformulation I (6)	S>S
Reformulation II (7)	S>Be
Reformulation II (8)	S>F

3. Measuring protocols

With a single method of segmenting and coding protocols it is possible to have a unified set of measurements across all protocols.

A number of measurement techniques are employed to obtain information from the two data sets of the segmented protocol and its syntactic and semantic linkographs. It is on the basis of the information produced by these techniques that comparisons between the differences in design cognition can be made.

Standard Statistical Analysis

The statistical analyses can be used to compare the results of one protocol with another. Despite the extensive use of statistical analysis in traditional coding schemes, the ad hoc nature of the schemes does not allow for comparisons between different cases and across different domains. On the other hand, the ontological basis of the FBS coding scheme allows for comparative studies of the statistical results obtained from different cases of design protocols.

The dynamic nature of designing can be measured by using window of a fixed number of segments and the statistical analysis carried out for that window as it commences at the beginning of the session, with its left edge at segment 1, and then moves a single segment over with the analysis repeated. The movement of the window a single segment at a time is repeated under the window's right edge hits the last segment of the protocol. For each window position an independent calculation is carried out and assigned to the central segment of that window. Putting the result of calculations together, a dynamic model is produced that shows the changing values of the issues and processes in the course of the design session.

Markov Models

Designer's strategies in terms of processes can be assessed by producing Markov models of the transitions between segments (Kemeny and Snell 1960; Norris 1998). A Markov model describes the probability of moving from one state to another in a stochastic system. This gives us the probability of a particular issue following another particular issue. This provides the foundation for cognitive insight terms of the transitions of cognitive tasks. We can do the same for linkographs. The dynamic Markov model can be generated using the same windowing technique as described for the general statistical analyses.

Cluster Analysis

If we remove all the links in a linkograph and only consider the nodes, we obtain nodes in a two-dimensional space. Treating each node as a point in the X-Y plane we can statistically describe a linkograph in terms of the mean values of X and Y – that is the centroid or the average position of all the nodes, and their deviations in the X and Y axes.

The total number of nodes indicates the level of saturation of a linkograph. Normalizing this number against the number of links will be the link index as described by Goldschmidt (1995). A higher mean value of X implies that more nodes appear at the end of a session and a lower value suggests that more nodes are present in the beginning of the session. A higher mean value of Y indicates longer linking lengths. The standard deviations show how concentrated the nodes are clustered around the means.

First passage model

A first passage model (sometimes called a first passage event model) (Kemeny and Shnell 1960) measures the average number of segments that a designer traverses before returning to the same issue. This is a measure of the designer's focus on an issue. It can be measured within a single protocol as an overall measure or using dividing up the protocol to determine changes in behavior during a protocol. As a measure it can be used to compare different protocols.

Entropy models

Further understanding about the behavior of designers can be obtained by examining the information content of their protocols. Shannon entropy (Shannon 1948) can be used to measure the information in a linkograph or a subgraph of a linkograph. In Shannon's information theory, the amount of information carried by a message or symbol is based on the probability of its outcomes. The more stochastic a system is, the more informative is the definition of its state. By measuring the entropy of semantic linkographs from different design sessions, Kan and Gero (2009) argued that there is a potential relation between the productivity of design activities and the entropy of their corresponding linkographs. Using the same idea about incrementally sliding a window along the design session, the dynamic entropy of the session can be measured. The dynamic entropy only takes the structure of the linkographs into account and currently ignores the codes in the segments. It is hypothesized that information entropy is related to fixation, commitment, divergence and convergence in designing.

4. LINKOgrapher – a measurement tool

4.1 LINKOgrapher

The production of the coded segments from the verbal and video protocol is a labor-intensive task, as is the production of the linkograph. Attempts have been made to automate some of the manual tasks. However, these have not yet produced a successful automated or even a semi-automated approach. The manual analysis of the coded segments and the linkograph is also a labor-intensive task. With an agreed set of analysis methods it becomes possible to consolidate the analysis methods into a single computational tool that takes as input the coded segments and the linkograph of a protocol and produces the results of the analysis in a portable form.

LINKOgrapher (Gero et al 2011) is one such consolidated measurement tool that carries out the following:

- standard statistical analyses
    - issues distribution
    - dynamic issues distribution
    - process distribution
    - dynamic process distribution
- Markov model generation
- dynamic Markov model generation
- entropy model generation
- dynamic entropy model generation
- dynamic entropy model generation
- drawing of linkograph

4.2 Typical results from LINKOgrapher

LINKOgrapher outputs its results in both graphical and numerical forms. Figure 3 show a screensho of the interface with its graphical output. Figures 4 to 7 show typical graphical output of some of the results from a protocol of 1,280 segments.

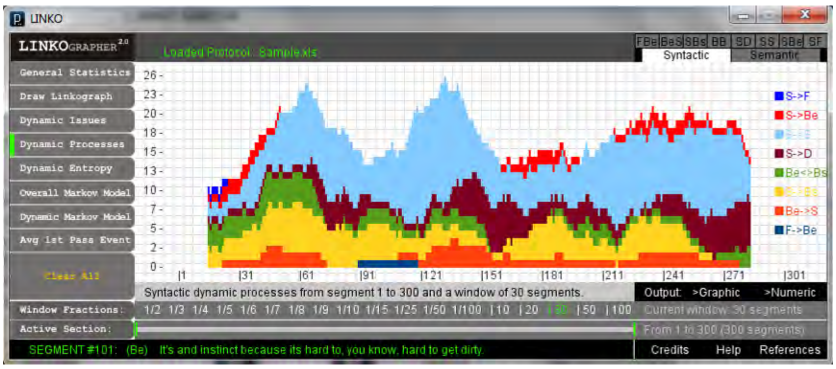
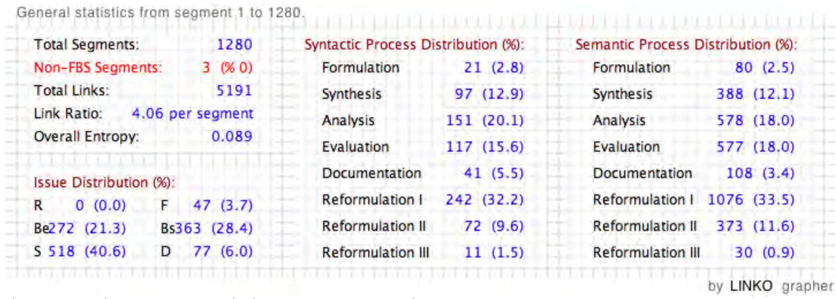


Figure 3 Screenshot of LINKOgrapher toolk showing interface and graphical output


General statistics from segment 1 to 1280.

Total Segments:	1280	Syntactic Process Distribution (%):		Semantic Process Distribution (%):	
Non-FBS Segments:	3 (% 0)	Formulation	21 (2.8)	Formulation	80 (2.5)
Total Links:	5191	Synthesis	97 (12.9)	Synthesis	388 (12.1)
Link Ratio:	4.06 per segment	Analysis	151 (20.1)	Analysis	578 (18.0)
Overall Entropy:	0.089	Evaluation	117 (15.6)	Evaluation	577 (18.0)
		Documentation	41 (5.5)	Documentation	108 (3.4)
Issue Distribution (%):		Reformulation I	242 (32.2)	Reformulation I	1076 (33.5)
R 0 (0.0)	F 47 (3.7)	Reformulation II	72 (9.6)	Reformulation II	373 (11.6)
Be272 (21.3)	Bs363 (28.4)	Reformulation III	11 (1.5)	Reformulation III	30 (0.9)
S 518 (40.6)	D 77 (6.0)				

by LINKO grapher

Figure 4 Typical tabular statistics presented as an image

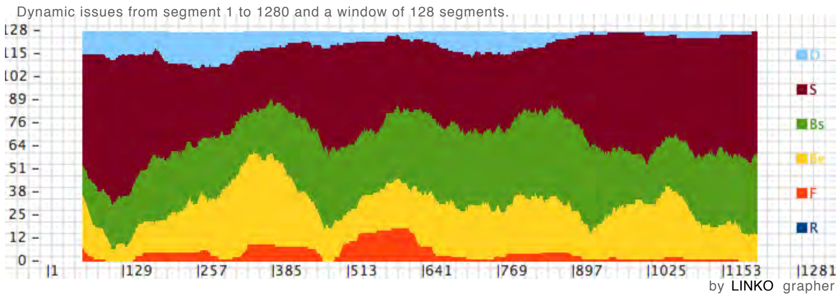


Figure 5 Dynamic issues showing the distribution of design issues across a protocol of 1,280 segments with a window 1/10th of the length of the protocol.

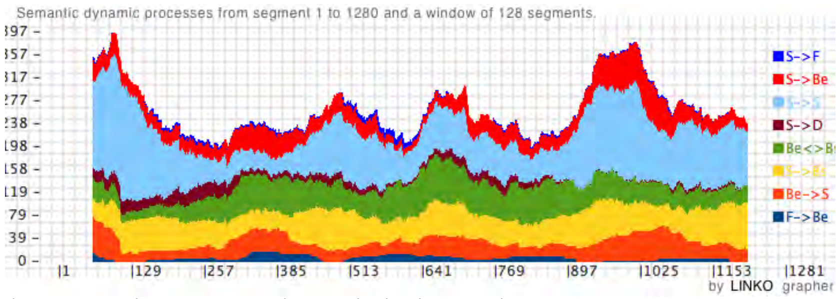


Figure 6 Dynamic processes showing the distribution of design processes across a protocol of 1,280 segments with a window 1/10th of the length of the protocol.

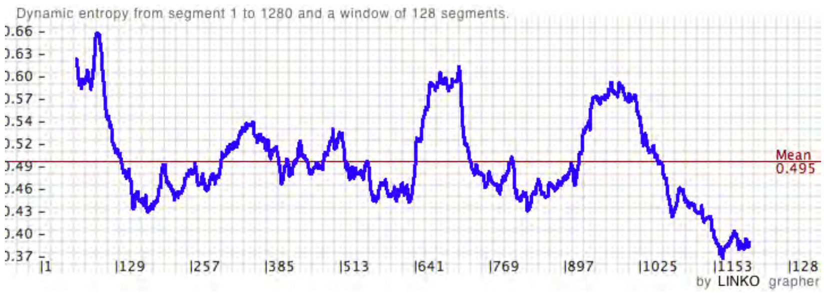


Figure 7 Dynamic entropy showing the distribution of entropy across a protocol of 1,280 segments with a window 1/10th of the length of the protocol.

The graphical form of the results provides opportunities for qualitative analyses. Associated with each measurement, in addition to the graphical output, is a numerical result with which further statistical analyses can be carried out.

5. Discussion

The lack of any common approach to the analysis of protocols of designers designing has limited the utility of the results. Although each researcher and research group can draw conclusions from their own results and make those conclusions available in a qualitative form this does not allow one researcher to build on the results of other researchers. It prevents the direct comparison of results.

Two classes of commonality are required for any empirical field to progress: commonality of representational description and commonality of measurement.
Commonality of representational description: requires an underlying ontology that provides a framework for the knowledge in the field being studied. This does not imply that there is a unique ontology for a field, only that without any ontology it becomes difficult or even impossible to describe the activities and events in that field in a form that can be understood and used by others. Any field will have multiple ontologies to capture its richness and the richness in the cognition of the researchers. This is largely lacking in design cognition research.
Commonality of measurement: is more usual in design cognition research but even here there is a lack of commonly utilized measurements. Whilst most researchers use descriptive statistics to provide a robust measurement very few use these statistics to attempt to describe the dynamic nature of designing. Even fewer use dynamic statistics or other richer measurements.

Through the use of a common ontology with a common measurement it is possible to make direct comparisons between results from different research programs. Figure 8 shows the comparison of design issues distributions in two disparate domains: architecture and software, where both protocols were analysed using a common ontologically-based coding scheme to code the protocol and a common measurement.

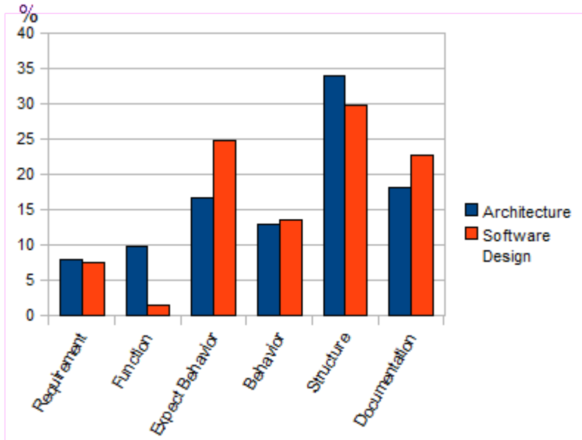


Figure 8 Comparison between architects and software designers of the distributions of issues.

Figure 9 shows the comparison of design process distribution in two disparate domains: architecture and software, where both protocols were analysed using the same common ontologically-based coding scheme and the same common measurement, which then makes direct comparison possible.

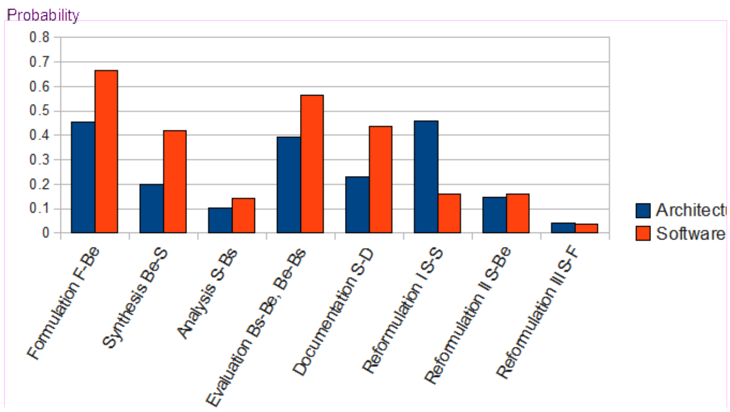


Figure 9 Comparison between architects and software designers of the distributions of design processes.

With commonly agreed analysis tools it becomes possible to disassociate the analysis from the researcher, from the task and from the environment of the task. This will have the effect of allowing results from the following situations to be compared:

- cognitive behavior differences between professional designers and student designers
- cognitive behavior differences between novice and expert designers

- cognitive behavior differences due to the use of tools and the use of different tools
- cognitive behavior differences due to design education
- cognitive behavior differences between individuals and design teams
- cognitive behavior differences due to gender
- cognitive behavior differences when designing in different disciplines.

For any science to progress it must build on the work of others in the field. Design cognition is currently hampered by its inability to do this.

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