Chapter 2
Background

This chapter provides a critical analysis of the relevant literature concerning the study of designers, protocol studies of designers and the measurement of designing. It defines the scope of the material in this book and clarifies terminologies such as creativity, design, designing, design collaboration and design assessment which are used in subsequent chapters. Various models and theories about design have been developed, and different claims have been made, based on case studies, concerning the creativity and quality of design. Instead of reviewing these models and claims, the focus of this chapter concerns methods of inquiry.

2.1 Studying Designers

Designing is one of the most significant intentional acts of human beings and is viewed as one of the most complex of human endeavours. Positions and philosophies of "what is design" determine how it is studied. Many designers develop their own philosophy and style. Various design strategies are available, such as using a first principle to find design solutions, analogies and metaphors, previous cases, delaying decisions until a design emerges, interacting to stimulate ideas, and so forth. Herbert Simon's classic work on artificial intelligence (Simon 1969) had a strong influence on design research; "designing as problem solving dominated the thinking of design researchers" (Gero 2007, p. 17). Others researchers (e.g., Cross 2007a; Jones 1970) viewed designing as a cross disciplinary field that embraces the humanities, the sciences, mathematics and art.

This book argues that the study of designers can be empirically based and yields an understanding of the cognition of designers. The methods to study the cognition of designers fall into five methodological categories: questionnaires and interviews (Cross and Cross 1998; Lawson 1997; Murty 2006); input-output experiments (where the designer is treated as a black box which produces the behaviors in the

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outputs for changes in inputs) (Purcell et al. 1993), anthropological studies (Lopez-Mesa and Thompson 2006), introspection (Galle and Kovacs 1992) and protocol studies. Protocol studies can be further divided into retrospective protocol studies (Suwa et al. 2000), and concurrent protocol studies (Eastman 1970). Protocol analysis is currently the useful method of studying designers (Cross et al. 1996a).

2.1.1 Protocol Analysis

Protocol data, based on samples of observations, are essentially qualitative. Ericsson and Simon (1993) laid the foundation of using verbal protocols, concurrent reporting, as quantitative data to study thought processes; van Someren et al. (1994) provided the theoretical background and a practical guide for the study and modelling of cognitive processes. They assumed a simple human cognitive model, Fig. 2.1, to develop the validly of verbal reports. The arrows in the diagram represent five different cognitive processes: perception (from sensory to working memory), retrieval (from long-term memory to working memory), construction (within working memory), storage (from working memory to long-term memory), and verbalisation (from working memory to protocols). The sources of invalid and incomplete verbal data were identified as being disturbance of the thought process, memory errors and the interpretation of the cognitive process. Their study also provided some practical guidance on how to obtain "good" protocols during experiments, such as taking care of subjects' feelings by offering assurances that their privacy would be protected; giving clear instructions to the participants; keeping the participants "thinking aloud", without disturbing or forcing them to interpret; and arranging a warm-up session involving similar tasks, to encouraged the participants to practice their verbalising concurrently.

The disadvantages of concurrent reporting are: (1) it slows down the thought process; (2) it does not review the whole thought process when the participants stop verbalising or use imagery only; (3) it impairs reasoning for those participants who cannot verbalise and reason simultaneously; and (4) there are subjective elements in the coding of concurrent reporting.

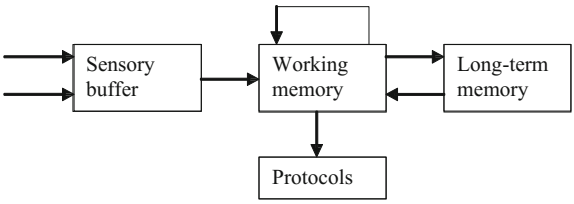

Fig. 2.1 van Someren's memory model (van Someren et al. 1994)

The fourth drawback can be improved by techniques such as inter-coder arbitration. Retrospective reporting with visual aids can prevent any slowing down of participants' reasoning while verbalising. These visual aids include the artefacts that the participant produced and the video recording of the participant designing.

The study of design thinking has been characterised as a method somewhere between the hard sciences and the social sciences (Cross 2007b). Protocol analysis has been used to identify different design activity, reveal different mental models and the knowledge structures of designers, as well as to investigate the perceptual aspects of sketching and designing (Atman et al. 2007; Tang 2002; Yilmaz et al. 2015). According to Akin (1998) the first formal protocol analysis of designing was conducted by Eastman (1970). Eastman's study contributed to the current understanding of what designers do when they design in the form of an information process model. Eastman viewed designing as a process whereby problems are identified and alternative solutions are tested. This view was challenged by a view of designing as a reflective conversation with material (Schon and Wiggins 1992) in which the basic structure is an interaction between designing and discovering.

Protocol Analysis in Different Design Domain

Besides the architecture design domain that Charles Eastman and Donald Schon applied protocol analysis to investigate design activities, researchers in other domains also use this technique to examine designing. In engineering design education, Atman and Bursic (1998) used protocol analysis as a tool to assess student's design process so as to evaluate the impact of changes in engineering education program so as to improve the way open-end design is being taught.

In engineering systems design, Ennis and Gyeszly (1991) studied six experienced designers solving engineering packaging problems. Verbal protocol analysis was used to identify how the designers introduced information or knowledge into the design process. They found that gathering information was a crucial approach for these expert designers to solve design problems and generate design ideas.

Hughes and Parkes (2003) surveyed the use of protocol analysis in software engineering research from the 1980s to 2003. Their conclusion was that the protocol analysis technique "has contributed towards the development and testing of models of the information processing during the software engineering process, particularly those relating to software design and comprehension" (Hughes and Parkes 2003, p. 138). However they also found difficulties associated with this method, they included: "(1) the effort of devising a valid and reliable encoding scheme; (2) the time-consuming nature of the encoding process; and (3) the problem of comparing results from researchers who have applied different encoding schemes" (Hughes and Parkes 2003, p. 138).

Process-and Content-Oriented Protocol Analysis

Dorst and Dijkhuis (1995) suggested that there are two types of analysis in protocol studies, namely, process- and content-oriented protocol analysis. Each captures the two different paradigms mentioned earlier—the information processing model and the reflection in action model. Usually the think-aloud or concurrent protocol is

used for process-oriented analysis, in which the processing of information is the focus. The retrospective protocol is often used for content-oriented analysis, in which the focus is on the content of designing. However, increasingly both protocol methods are used for both purposes.

Tang (2002) carried out a detailed empirical comparison between the retrospective and the concurrent protocols. He found they were similar in terms of quantity and quality; quantity related to the number of segments. In terms of quality, the concurrent protocols revealed more information related to the functional aspect of designing, whereas the retrospective protocols revealed more information about producing solutions and evaluation. There are many differences in the approaches to methods and the coding schemes coupled with specific aspects of both content and process-oriented protocol studies. The next subsection reviews a number of issues related to the commonly used protocol analysis of designing.

2.1.2 Measurement of Design Protocols

The analysis of design protocols, both content- and process-oriented, or any type of design protocol analysis usually involves statistical methods.

Unit of Analysis

The unit of analysis varies according to the objectives and foci of studies. It can be individual participants (in the study of design teams), sessions, episodes, code categories, or even each segment/utterance. In the classical method of studying design protocol, van Someren et al. (1994) classified the procedures into five steps: conducting experiments, transcribing protocols, parsing segments, encoding according to a coding scheme, and interpreting the encoded protocols. The first step is derived from the research aim and method.

Diversity in Segmenting

In parsing segments, there are different ways to segment protocols, depending on the objectives and scope of the study. For instance, protocols can be segmented according to instances of processes in order to study the frequencies of processes. Ericsson and Simon (1993) suggested that appropriate cues for segmentation are pauses, intonation, and contours, which correspond to their information processing model. Gunther et al. (1996) along with Dorst and Dijkhuis (1996), used a fixed 15-second time-scale. The advantage of this method is that it requires no interpretation; hence it quickly segments the protocols. However, the obvious problem with a fixed time-scale is that it may cut in the middle of a statement, which could make the coding difficult; therefore additional criteria are required to handle these cases.

Another way of segmenting protocols relates to the designers' lines of intentions or actions (Gero and McNeill 1998; Suwa et al. 1998). In this category, there are also differences in whether the categorisation affects the segmentation. In Gero and

McNeill (1998), one sub-category corresponds to one segment. On the other hand, Suwa et al. (1998) proposed that one segment might contain several sub-categories.

Yet another way to segment design protocols is by "design moves", which Goldschmidt (1990) introduced as "the smallest coherent operation detectable in design activity" (Goldschmidt 1992) but Perry and Krippendorff (2013) in their study found that identifying the boundaries of the move was not reliable with student coders even with training.

Diversity in Coding Schemes

Code categories are defined by a coding scheme, many of which have been developed for use with design protocols. All such schemes are based on particular views of the activity of designing, and most are unique to the data to which they are applied. For example, to document engineering student design process, the coding scheme (Atman and Bursic 1998) used contains four main variables: design step, information processed, activity and object. Within each variable there are sub-categories of codes, for example in the design step there codes for need, problem definition, gather information, generate ideas, modelling, feasibility analysis, evaluation, decision, communication and implementation.

In Hughes and Parkes' (2003) survey of protocol analysis in software engineering research, they grouped specific sub-domain or activities related to: requirement analysis, design meetings, debugging, re-engineering, corrective maintenance and team reviews; within which the study areas were focused in team work, novice vs expert, debugging strategies, domain knowledge, etc. They found that early work focused efforts to devise a cognitive model of programming behaviour, and gave some attention to different strategies used with different programing languages. Attention moved then to examine the software design process and use of tools to support the designing. Later research studied alternative methodologies and modelling design processes. They also found two recurring themes: (1) an investigation of the design process and (2) a comparison of behaviours between levels of expertise. They noticed that though specific themes have recurred throughout the two decades that they surveyed, no common coding scheme has been developed that can be applied in a range of different circumstances. They also evaluated a general-purpose coding scheme, 'A Flexible Expandable Coding Scheme' (AFECS) (von Mayrhauser and Lang 1999), and found it is helpful as a template to determine the basic structure of a coding scheme but the actual coding scheme constitute a fraction of a customised general-purpose coding scheme.

Gero and McNeill's (1998) developed one of the most comprehensive process-oriented coding schemes concerning designing, which contains multi-dimensional categories. One dimension of the categories concerns the designer's navigation within the problem domain with different levels of abstractions. Another dimension concerns the strategies used by the designer. Yet another dimension relates to the designer's reasoning about function, behaviour or structure.

Suwa et al.'s (1998) coding scheme is a good example of a content- oriented coding scheme. It was based on the human cognitive process sequence—sensorily, perceptually, and then the semantic categorisation of design actions into four

categories: (1) physical, corresponding to the sensory level, consists of categories of making depictions, examining previous depictions and other physical actions; (2) perceptual, corresponding to perceptual action, contains categories of attending to visual features, attending to spatial relations, and organising or comparing; (3) functional, contains categories of design artefacts: issues of interaction, and psychological reactions of people; and (4) conceptual, corresponding to the semantic, consists of categories such as making evaluations, establishing goals and retrieving knowledge. This coding scheme was not originally designed to study group or team designing.

All the above research suggested that it is difficult to have a general and efficient coding scheme to map different design situations and scenarios onto design processes because of the diversity of domains and various views of designing.

Design Teams

There is an increased interest in understanding team designing processes and activities. It is impractical to undertake retrospective studies when a design team consists of more than three members. Compared to individual designing, studies (Cross and Cross 1995; Gabriel 2000; Olson and Olson 2000; Zolin et al. 2004) have shown that there are a multiplicity of factors that contribute to or affect team designing. Some of these factors are role and relationship, trust, social skills, common ground, organisational context and socio-technical conditions. Most of these factors are underpinned by communication, either verbal or non-verbal. Cross et al. (1996a) suggested that the verbal communication of members provides indicative data on their cognitive activities.

The protocol analysis technique has been adopted to understand the interactions of design teams (Cross and Cross 1996; Mazijoglou et al. 1996; Stempfle and Badke-Schaub 2002) and the behaviour of teams (Goldschmidt 1996; Valkenburg and Dorst 1998). Bly and Minneman (1990), along with other protocol studies (Gabriel 2000; van der Lugt 2003) suggested that with the introduction of technology, designers will adapt their activities accordingly. Goldschmidt (1996) and van der Lugt (2003) both used linkography (explained in the next section, Sect. 2.1.3) as a base for their studies. Valkenburg and Dorst (1998) used a similar, albeit differently presented, method to trace reflection in action by relating (rather than linking) segments in a protocol in terms of naming, framing, moving and reflecting.

Although some researchers use similar methods, there is no unified framework that can be applied to the study of design teams. The existing protocol analysis methods developed to study designers may need to be revisited if we are to understand the dynamics of team designing and then compare them to individual designing.

Statistical Analysis of Design Protocol

In statistical terms, the coded segments of protocol data usually contain two parts: the qualitative part with categorical (nominal) data and the quantitative part concerning duration (time). There are generally two types of analysis—descriptive statistics and inferential statistics—both based on the assumption of distribution.

Descriptive statistics are used to summarise the protocol data—usually in the form of charts and tables. This kind of analysis can reveal how the designers spent their time. For example, Maher et al. (2006) used descriptive statistics to study the impact of a collaborative virtual environment on design behaviour. They found that the designers spent the largest percentage of their time focused on communicating about the design task and on actions to produce an external representation in all environments.

Inferential statistics are used to test models of designing from protocol data. For example, hypothesis-testing can verify proposed models of designing. McNeill et al. (1998) used a *t* test on the hypothesis that the design process moves from a design requirement, expressed in terms of function, to a design description couched in structural terms. They also used linear regression to test the transition relationship between "evaluation to analysis". Hypothesis-testing was also used to compare designers working in different conditions, or to compare different designers working in similar conditions. The chi-square test is another common tool used in protocol analysis for hypothesis testing. It tests if the frequency distribution of certain coding categories observed in a protocol is consistent with a particular theoretical distribution. Readers can refer to standard text on statistics for the concepts and conditions behind these tests.

Relationships among variables and categories can also be explored with a statistical method. For example, Kvan and Yunyan (2004) correlated students' learning styles with their performance in the design studio. Kavakli and Gero (2002) used a correlation coefficient to obtain the structures of cognitive actions and then compare them between an expert and a novice designer. In many cases variance analysis (ANOVA) was used to carry out testing and comparisons among different sets of protocol data to confirm findings.

The analysis and the interpretation of design protocol are heavily reliant on statistical methods. Recently, information theory has been applied in statistical inference (MacKay 2003). Although it was proposed to model qualitative data in the 1980s (Krippendorff 1986), it has not been used in protocol analysis. Exploring the application of information theory may provide new insights into design protocol analysis.

Time Line of Design Activities

Many researchers have observed that the design activities change during a design session. Goldschmidt (1995) divided design sessions into episodes and reported the differences in the interconnectivity of ideas in those episodes. Gero and McNeill (1998) found that designers spent more time reasoning about the function and behaviour at the beginning of a session and spent more time reasoning about the structure towards the end of a session. Time series analysis in the protocol study of designers is rare. In other fields, such as the behavioural sciences, sequential analysis has been used to model interaction patterns (Gottman and Roy 1983; Bakeman and Gottman 1997).

Summary

In summary, the unit of analysis featured in protocol studies of designers varies because it is determined by the aim of the study (Hay et al. 2016). Without the same unit of analysis, there is no standardisation of the coding scheme or segmentation. This makes it difficult to compare the results of different studies, even with the same set of data. Most of the coding schemes are unique to the protocol data and cannot be reused in new circumstances, which impedes the accumulation of knowledge in this field. The interpretation of design protocol is heavily based on simple statistical measurements of the quantity of encoded data.

2.1.3 Linkography

Linkography takes a very different approach than other protocol analysis methods. Goldschmidt (1990) introduced linkography to protocol analysis. Briefly stated, instead of classifying the segments, it studies the interconnection among the segments. This approach considers both the content and the process. The segments are treated as "design moves." The definition of a design move together with an example of constructing a linkograph is provided in the next chapter, Sect. 3.1. Latter, Goldschmidt and Tatsa (2005, p. 595) stated:

> Linkography is based on the premise that effective reasoning in a creative endeavour must perforce aim at first mining and then relating to one another the many items of data that are relevant to the task.

A linkograph is constructed by discerning the relationships among the moves to form links. It can be seen as a graphical representation of a design session that traces the associations of every design move. The design process can then be examined in terms of the patterns in the linkograph that display the structure of design reasoning. Three distinct patterns were identified: chunk, a group of moves that are almost exclusively linked among themselves; web, a large number of links among a relatively small number of moves; and sawtooth track, a special sequence of linked moves. Goldschmidt also identified two types of links, namely, backlinks and forelinks. Backlinks are links of moves that connect to previous moves and forelinks are links of moves that connect to subsequent moves. The next chapter explains their respective differences.

Analysis of Linkographs

The progress of a design session is made observable through the analysis of linkographs. The analyses of chunk, web and sawtooth patterns is conducted qualitatively. Linkography has been used to investigate the structure of design idea generation processes and to compare design productivity (Goldschmidt 1990, 1992, 1995). The primary quantitative comparison in these studies was by link index and critical moves. Link index, also known as link density, refers to the number of links

divided by the number of moves. Critical moves are design moves that are rich in links, usually more than five links. The combined critical moves of a sequence describe its critical path. Goldschmidt used these numbers and the critical path to benchmark the productivity of a design session.

Applications of Linkographs

Goldschmidt's linkography was used by van der Lugt (2003) to trace the design idea generation process and to correlate the creative qualities of ideas with the degree of their integration. He conducted four experiments, idea generation sessions under different conditions, and asked participants to appraise the ideas after the sessions. He extended linkography by identifying the link types in three categories: supplementary, modification or tangential links that correspond to small alterations of ideas, the same direction of ideas, or a different direction of ideas respectively. He found that a well-integrated creative process has a large network of links, a low level of self-links, and a balance of link types.

Dorst (2003) used linkographs to trace the linking behaviour of designers with regard to design problems and design solutions to reveal the reflective practice of designers.

Study of Design Teams by Linkography

Linkography was used to study design teams by Goldschmidt (1995) and van der Lugt (2003). Goldschmidt (1995) compared the productivity of the design processes of an individual and a team. Participants were asked to design a bicycle carrier for a backpack. The team consisted of three designers and conversational turn-taking was used to segment protocol; an utterance by one of the designers was defined as one move. Critical moves analysis and link index provided a quantitative means to compare the "solo design" and the "team effort." The experiments conducted by van der Lugt (2003) consisted of five advanced product design students. Linkographs were generated to study the effects of sketches in idea generation meetings. These studies indicate that this technique is not dependent on the number of participants.

2.2 Design: Process or Artefacts

This section presents a particular view of design research. A design (a noun) is usually described as a set of decisions that determines the relationships among geometries, materials and performance. Although there are different variables in different domains, the central activities of designing (a verb) remain very similar. The authors assume that these activities, notwithstanding some claims to the contrary, are scientifically observable. They include thinking and knowing (Cross 2007a), free-hand sketching and interactions (Lawson and Loke 1997; Schön and Wiggins 1992), the social construction of design solutions (Minneman 1991) and designing-by-making (Jones 1970). Some activities are harder to observe than others are.

This book is not about the exploration of design methods; rather, it explores the methods that can be used to study design activities. Certain views of designing will affect how studies are conducted. For example, within the information processing model of designing, some have placed more stress on the internal and external representation of information (Eastman 2001), whereas others emphasise the interaction of information (Gero and Kannengiesser 2000). These two different views have fostered their own distinct research streams. For example, Badke-Schaub et al. (2007) followed the former model to assess the development of shared representations in a design team, whereas Suwa et al. (2000) followed the latter model to investigate situated inventions and unexpected discoveries.

This book considers that designing involves some acts of manipulation of available material with knowledge to fulfil a set of requirements by imbuing them with appropriate qualities. The set of requirements may change during designing. These acts of manipulation are considered to be transformative processes. The available material can be viewed through the lenses of function, behaviour and structure. Chapter 3, Sect. 3.4, provides a detailed explanation. Appropriate qualities can be evaluated subjectively as well as by measurement.

2.2.1 Design Ideas

It is commonly held that good design ideas are essential for good design outcome. Linkography studies have suggested that good ideas have many interconnections with other ideas. Chapter 3, Sect. 3.3.2 challenges the supposition that more links are better by arguing that if there are too many links the ideas will be too similar, leading to less interesting designs. This might also indicate early fixation. Although Cross (2007a) suggested that fixation is not necessarily undesirable in the study of expert designers, the authors speculate that novel ideas are desirable in designing. It is conjectured that the study of a linkography may review the processes of a good design. Gero (2010) used linkography and some of the techniques described in this book to measure fixation and commitment while designing.

2.2.2 Design Process and Design Outcome Assessment

A design is generally assessed according to its outcome. The assessment criteria might vary in different domains. However, creativity remains one of the most important criteria. Other criteria include usability, aesthetic appeal, practicability, performance and functionality. However, what are the factors in the design process that constitute a good design?

Studies have shown that there are behavioural differences between design experts and novices during designing (Kavakli and Gero 2002, 2003; Cross 2004). Educators will benefit from knowing which design processes will yield desirable

design outcomes. Yukhina (2007) examined the effects of cognitive abilities and learning styles on design students' academic performance. She found that visualisation abilities are the best predictors of academic performance. However, her study did not find any consistent correlation between the design processes (using protocol analysis with Gero and McNeill's (1998) coding scheme) and learning styles or cognitive abilities. As mentioned in Chap. 1, there have also been studies that have attempted to find the relationship between design performance and the integration of ideas and design strategies (Goldschmidt 1992; Kruger and Cross 2006). They too found no compelling evidence to directly associate the design process with the design outcome.

2.3 Conclusions

This brief review suggests that the quantitative methods for analysing design protocols are the primary tool to study the design process. Descriptive statistics and correlations are the dominant tools for analysis. We propose an exploration of other methods for analysis, such as information theory and Markov chains.

Many coding schemes have been developed for use with design protocols. They tend to be based on particular views of the activity of designing. Many of them are unique to the data to which they are applied. This limits the applicability of the results obtained. Where more general coding shemes have been attempted, they lacked sufficient generality that would make it feasible to reuse them in widely varying circumstances. Linkography, on the other hand, does not have any coding scheme and has been successfully used in studies of team designing activities. This study seeks to determine the potential for an extension of linkography as an a analysis tool.

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