A Functional Analysis of the Role of Visualisation in Architectural Conceptual Design

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Abstract

The view that visual reasoning in design is facilitated by external visualisation, specifically sketching, is based on both anecdotal evidence and empirical observations. The purpose of the current research is to investigate the relationship between visual reasoning, via sketches and the development of the early conceptual stages of the design process. Thus, the paper focuses on an analysis of visualising in conceptual design problem solving. The application of a new taxonomy throws light on experts' use of external visualisations. The results indicate that there are 'shifts in focus' with regards to the functional use of visualisations in architectural conceptual design.

1. Introduction

Design has traditionally been viewed as the drawing of objects that are then built or manufactured. There has traditionally been two distinct ways in which to describe the process of designing. The first perceives it essentially as a rational, logical, sequential process intended to solve problems. Thus, for the term “design process” we can also read “problem-solving process”. The problem solving approach means looking at design as a search process, in which the scope of the steps taken towards a solution is limited, for example by the information processing capacity of the designer [1][4]. The second way to consider design is to perceive it as a process of reflection in action [27], where each design problem is unique. The approach is one that emphasises the designers ‘reflective conversation with the situation’.

Whether one views designing as a reflective conversation with the attributes of the problem space or as a logical sequential search process, research has shown that design problem solving is a process that can be accentuated through the use of external representations. Research evidence from; design science[5][6][7][12][18], design education and cognitive science[8][10][11][13][24] suggests that sketching is a fundamental activity within the design process. Therefore, mapping designers’ use of external visualisations to their cognitive processing of design information would seem to be essential for the understanding of design problem solving. It is a process that needs to be examined in greater detail.

A starting point for current research discussed in this paper was research conducted by Verstijnen [26]. She showed that in an experimental shape recognition task, which compared experts and novice use of sketches, only experts were able to use visualizations to their advantage. Thus, one may ask what domain specific procedures are used by expert architects when visualizing a design problem space? The research sets out to establish the functional attributes of external visualisations and the analysis of the results reflect this perspective. It could be argued that a functional model of external visualisations in conceptual design may not provide the means by which to assess how sketches facilitate problem solving. However, a functional model of the acquisition of domain-specific knowledge should enable us to understand why designers need to visualise in architectural problem solving, which is the focus of this paper.

This paper emphasises the importance of external visualisations. A new taxonomy, built on architectural domain-specific procedures, has been developed. The taxonomy deals with The Retrospective Analysis of the Designers Cognitive Processes (RADCOP), with specific reference to the function of their visualisations. The

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2 The term visualization is defined as the visual representation of information.
validity of the taxonomy has been tested using 5 encoders and it has been applied to the verbalisations of 5 experts architects.

Purcell and Gero[21] identified five qualitative themes from the literature on design sketching. One of these themes embodied the notion that sketches bring about a 'focus shift' and that these shifts are desirable because they aid the processing of conceptual design knowledge, in new and novel ways. Research conducted by Suwa and Tversky[24] analysed designers' attention and their shift in focus when dealing with tokens or the attributes of the design task. The current research has focused on establishing the extent to which the interrelationships between different types of knowledge associated with external visualisations strategies (i.e reasoning, resolution, emergence) changed over the period of the design task and whether qualitative themes could be elicited from the data. Thus, the current research can be differentiated from prior research because the granularity of the analysis is at the level of identifying the problem-solving strategies, rather than at the token, attribute (specific domain specific knowledge) level of analysis. The current research assess the data in terms of how external visualisations are used over the whole design task, the strategies that are involved, rather than the content of the information contained within each focus shift.

2. Describing Visualisation in Design Problem Solving

The design process begins with the identification and analysis of a problem or need and proceeds through a structured sequence of formulating, evaluating and solution finding. It is a process in which information is researched and ideas explored and evaluated, until the optimum solution to the problem or need is devised.

Process models of the design have traditionally considered conceptual designing in the early phases of the design process, where information is researched and ideas are explored. At this stage designers rely on external representations: sketches, schematic diagrams and notes. Lawson[15] has described how sketches, as external visualisations, are not always for others in the community, rather they are also used as a form of visual reasoning. Thus, the designer may not be concerned with the production of a drawing that explains itself or the drawing of an object that is totally resolved. Rather, sketching is used as a working tool that aids the designers' manipulation of the constraints of the design problem. Wiggins and Schon[27] and Akin[10][3], emphasise this point when they describe the need to sketch in order to conceptualise an architectural design problem space. Ullman, Wood and Craig[22] and Lawson[15] also suggest that designers, in general, are know for not being able to think without making marks on paper. Alexander[3] goes some way to explain the designers need to sketch. He noted that in some instances conflicting requirements can be calculated in ones head. However, as design problems reach levels of complexity, the complexity of the problem will defeat the designer unless a simple way of writing it down is found that enables the problem-space to be broken it into smaller problems. A reoccurring theme in the literature is the proposition that visualisations may act as external memory aids, facilitating the processing of the acquisition of new information[14],[5] and at the same time the process of visualising may facilitate the designer in the perception of different structures, suggesting a re-representation of the problem space[22]. Lastly, Ullman, Wood and Craig [23] proposed that this manipulation of information in a designer's head can only be studied through an analysis of his or her representation of these features as written text, words, drawing or gestures.

3. Previous Methods of Analysis

Analysis of the design process, according to Dorst and Dijkhuys[9] can be classified into two categories: the process-oriented approach and the context-orientated approach. The first approach is based on the information-processing paradigm. It describes design in terms of problem states, operators, plans, goals and strategies [3]. The second approach is more descriptive in nature, tries to reveal the content of the designers’ thoughts in terms of what they attend to, and the information they retrieve from memory. Suwa et al [22] consider the second approach to be the most appropriate when analysing how designers cognitively interact with their external visualisations. However, the approach is one which has until recently has been limited by the lack of taxonomies to describe the contents of the designers thoughts and visualisations.

Suwa et al [22] recently developed a taxonomy for examining the contents of the designers cognitive process based on Suwa and Tversky’s[24] content-orientated taxonomy. A taxonomy which was itself based on Goldschmidt’s[13] proposition that design reasoning is characterised by the designers oscillation between two modes of thought: ‘seeing as’ which deals with figural arrangements and ‘seeing that’ which refers to non-figural issues that need to be resolved. Thus, the major dichotomy in Suwa et al [22] classification was between visual and non-visual information. Four categories of ‘actions’ were derived physical and perceptual, which relates to visual information, functional and conceptual,
which relates to non-visual information. The categories were sub-categorised into numerous sub-categories.

The problems with Suwa’s [23] taxonomy are two fold. Firstly, the coding of the protocol the content and the processing of information is inextricably linked. The taxonomy is half way between, describing the content of the design protocols in terms of the ‘what’ designers draw (i.e. the rectangle for the parking), and describing how the designer processes the information. Secondly, and more importantly, the reliability of the coding for both Suwa et al [21] and Suwa and Tversky’s [24] has not as yet tested, either by using alternative encoders or by conducting more than one protocol study, using the taxonomy.

Like Suwa and Tversky’s [24]. Do and Gross [6], the authors (McFadzean et al) have previously suggested that designers sketching activity can be mapped to their cognitive processing of design information. The current research can be differentiated from prior research, for although it investigates the content of the visualization it focuses on the function of sketches in architectural design. This paper discusses the results of applying a new taxonomy of architectural design knowledge, to five expert architectural designers. It examines the how the approach has been used to construct a high level functional analysis of external visualisation in conceptual design, so that the designers evolution of the conceptual design problem space can be traced.

Understanding complex aspects of design cognition, in more than an anecdotal way, requires rigorous methods of analysis. It has been suggested [17] that in order to investigate the use of external visualisations in design there is a need for more reliable methods for data capture, visualisation and interpretation. The authors have developed a computational method for capturing sketching activity and a method for visualising and analysing designers sketching behaviour. The method is referred to as Computational Sketch Analysis [19], [20]. It has been used, not only to analyse the production methods by which external visualisations are created, but also to capture designers’ retrospective reports of their sketching activity. Thus the computational method has been used in conjunction with an analysis of the verbal protocols. This paper uses the data collected from the CSA experiments and asks the question, why do expert architectural designers sketch? The focus of the paper is specifically on the analysis of the function of external visualisations in architectural conceptually problem solving.

5. A Laboratory Experiment and Data collection

5.1 Task and Subjects

The experimental set-up replicated a conventional sketching environment with additional facilities for data capture. An A3 graphics tablet with plain or tracing paper overlay plus a lead pencil allows the designer to sketch normally.

There are two forms of data capture:

1. The Data Capture program collects and time-stamps the graphical data generated during a design session.

2. Video recorders capture the context of the design actions and verbalisations of the designers.

Six CSA experiments were undertaken. Only participants (D1,D2,D3,D5,D6) who were architects with between 2 and 20 years of professional experience were considered relevant to the study. As D4 was an engineer their data was not analysed. The experiments were all identical, lasting about one hour and consisted of two tasks: a design task and a retrospective report task. The design task asked the participants to design a smoker’s lodge (an outdoor shelter for smokers) on a University campus. Participants were given a design brief, after which they were taken to a site that could potentially house the lodge. On returning they were asked to produce conceptual designs. The task was recorded using the 'Data Collector'. Following the design task, the designers reviewed their sketching activity using the Sketch Analyser and they were asked to report on what they were thinking when they were generating the visualisations [10].

6 Method of Analysis

6.1 Transferring Data into Protocol transcripts

The raw data was transferred into five protocol transcripts. The transcripts were segmented by pauses greater than 2 seconds. A pause greater than 2 seconds indicates that the successive statement probably provides information on a new perceived item. According to this method the protocols contained 103, 70, 33, 110, 70 segments for designers 1 to 5 respectively.

6.2 Identifying Design Suppositions

The research presented in this paper uses qualitative and quantitative approaches to analyse expert designers, complex interacting design thoughts in relation to their production methods for creating external visualisations. The data was inductive in nature. The coding systems used for the analysis of the verbal protocols emerged from
the data but was informed by the literature. It was based on the idea that the dialogue regarding the function of sketches could be coded. The functions are termed 'Design Suppositions'. A Design Supposition was defined as a group of words that made up a unit of sense or meaning, usually separated from the next Design Supposition by the end of an utterance. The transcripts of the designer’s retrospective reports were divided into separate ‘Design Suppositions’.

A detailed discussion and analysis of Design Suppositions is discussed by McFadzean, Cross and Johnson[16]. Nine Design Suppositions define the classification-encoding schema:

1. External memory aid: The designer discusses how memory for other design problems, concepts and objects with similar constraints to those of the present problem are recorded in order to later act as stimuli.
2. Emergence: The designer reports sketches are used to develop new ideas and aid in the emergence of new visual forms.
3. Constraints: The designer discusses how sketches are used to figure out how to arrange the available variables of the design problem, space such that the requirements of the domain are fulfilled.
4. Abstraction of the Design Problem: Designers' have the cognitive ability to deal with the ambiguity of the design problem space whilst they are able to comprehend the importance of resolving the ambiguity in such a way that the design problem space evolves towards a solution. From this assumption we created a problem definition category that describes the designers reasoning about the nature of the evolving design problem space as:
   a. An aspect of the design problem is ambiguous
   b. Only part of the design problem is resolved.
   c. An aspect of the design problem is never resolved
   d. Questions are used to rationalise the design problem.
   e. The design problem is consider at global level
   f. The design problem is consider at a local level
   g. The design proposal is abandoned
   h. The designer considers that a mistake has been made with regards to the design problem
5. Reasoning: Sketching provides the means to produce and explore visual representations of ideas. The design problem evolves when designers' reason and explore the design problem space using attributes relevant to the design problem space such as, dimensions, spatial layout, shape, structural properties and materials.
6. Problem defining/ Resolving: Problem resolution is a generic category that deals with the designers' decisions to accept, reject, suspend or refine attributes of the architectural design. The decision regarding an attribute does not necessarily have to be permanent.
7. Reflection: refers to the recording of the outcome of the designers’ reflections on past and future explorations, on the use of mental imagery.
8. External Representations: refers to the designer's discussion of how the sketches are constructed. For example, redrawing a previously drawn visual element, drawing over existing graphical marks.
9. External visualisation Problems: The designer indicates that there is a problem drawing or visualising the object in 2 or 3 dimensions or that there is a problem in drawing from memory.

An Example of a ‘Design Supposition’ is the use of sketches as an External Memory Aid. The classification-encoding schema suggests the following instance of such an event:

a. Exemplars are recalled from memory and either written or drawn so that they are stored as an external memory.
   b. The designer writes down a possible problem in order to deal with it later.
   c. The designer draws in order to aid recollection from memory.
   d. The designer writes in order to visualise and record a concept.
   e. The designer writes as a thought occurs.

6.3 Reliability of Taxonomy and Coding

Two questions were asked in order to verify the validity of the classification-encoding schema:

1. Can a predefined set of Design Suppositions account for the majority of the cognitive systems used in architectural problem solving?
2. Can Design Suppositions be applied consistently to a designer's retrospective report of their conceptual design activity?

Five individuals, referred to as encoders, read the first designers' (D1) transcript to identify coding categories of Design Suppositions and to develop optional definitions for each one. The transcripts and the emerging coding categories were re-read until the researchers felt that they had exhausted the raw data. Agreement between the encoders coding of the Design Suppositions was determined using Kendall’s coefficient of concordance.

The results of the statistical analysis of the data showed that the assessment of the participant's retrospective reports, in terms of the Design Suppositions classification-encoding schema, allows a rigorous means by which to encode architectural design verbal protocols.

6.4 Data Tabulation

Upon completion of the coding the frequencies of the different Design Suppositions were tabulated for each
designer, for the purposes of further comparison. Table 1 shows the tabulation of the data for design task.

<table>
<thead>
<tr>
<th>Classes of Design Suppositions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
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<tbody>
<tr>
<td>Designer 1</td>
<td>36</td>
<td>48</td>
<td>29</td>
<td>106</td>
<td>140</td>
<td>24</td>
<td>10</td>
<td>40</td>
<td>22</td>
</tr>
<tr>
<td>Designer 2</td>
<td>12</td>
<td>21</td>
<td>13</td>
<td>43</td>
<td>69</td>
<td>25</td>
<td>24</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Designer 3</td>
<td>4</td>
<td>4</td>
<td>17</td>
<td>18</td>
<td>40</td>
<td>27</td>
<td>6</td>
<td>3</td>
<td>0</td>
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<tr>
<td>Designer 5</td>
<td>38</td>
<td>30</td>
<td>42</td>
<td>65</td>
<td>139</td>
<td>13</td>
<td>10</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Designer 6</td>
<td>26</td>
<td>12</td>
<td>40</td>
<td>43</td>
<td>84</td>
<td>13</td>
<td>12</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 1 Frequency counts for the classes of Design Supposition, for the entire design task**

This paper will discuss the results of the analysis firstly in terms of the similarity of the individual designers, with regards to the retrospective reporting of the Design Suppositions. It will then interpret the findings in terms of a functional cognitive mapping.

**7. Results of the Protocol Analysis**

In accordance with the research question ‘Why do designers need to visualise during conceptual design’, the research measured the correlation between the designers in terms of their use of the Design Suppositions. Kendall’s coefficient of concordance was computed [21], in order to establish whether the expert architects exhibited any overall similarity in their use of the Design Suppositions over the design task. The frequency counts for the Design Suppositions (Table 1) where ranked separately for each designer, from 1 to 9, in order of the largest first (Table 2).

<table>
<thead>
<tr>
<th>Classes of Design Suppositions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designer 1</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>9</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Designer 2</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Designer 3</td>
<td>6.5</td>
<td>6.5</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Designer 5</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Designer 6</td>
<td>4</td>
<td>5.5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>5.5</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Sum</td>
<td>25.5</td>
<td>26</td>
<td>23</td>
<td>11</td>
<td>5</td>
<td>24</td>
<td>33</td>
<td>34</td>
<td>44</td>
</tr>
</tbody>
</table>

**Table 2 Ranks assigned to the classes of Design Supposition, for the entire design task**

If the designers used Design Suppositions in similar ways, then one class of Design Supposition would have a sum of 5. The next most frequently used class would have a sum of 10, and the least used class would have a sum of 45. If there were no agreement amongst the designers, as to their patterns of reasoning, then the sum would be approximately equal. Thus, the degree of agreement amongst the designers is reflected by the degree of variance amongst the sum of the ranks. Siegel [21] states that $W$, the coefficient of concordance, is a function of that degree of variance. For the data shown in Table 2, the rank mean is 25. $S=1100.5$, $W=0.7343$. As the number of classes of Design Suppositions (N) is larger than 7 the significance of the observed value of $W$ can be determined using the formula $K(N-1)W$.

The results show that when $W=0.7343$, there are 5 designers and 9 ranked classes $\chi^2$ equates to 29.37. Referencing the critical values of Chi Square (Siegel 1956, Appendix Table C) we find that $\chi^2=29.37$ (df=8) has a probability of occurrence under $H_o$ of $p<0.001$. Thus, it can be concluded with considerable assurance that the similarity between the five designers is higher than would be expected by chance. The results indicate that during the conceptual design task the expert designers used visualisations for similar purposes.

In order to validate this inference and to establish the purpose (function) of visualisations at periodic intervals in the design task a macro-analysis of the data was conducted. This macro-analysis was quantitative in nature and it was used as a springboard for a qualitative analysis of the individual differences between designers.

**7.1 The Shifting focus of Design Suppositions as a function of Time**

The data, for each designer, were divided into quartiles. The frequencies of the different Design Suppositions were tabulated and ranked for each designer. Kendall’s coefficient of concordance was applied to each quartile. In ascending order the value of $W$ for each quartile are as follows $W=0.79$, $\chi^2=31.6$, $p<0.001$. $W=0.62$, $\chi^2=24.8$, $p<0.01$. $W=0.48$, $\chi^2=19.2$, $p<0.05$ $W=0.78$, $\chi^2=31.2$, $p<0.001$.

The results show that in each quartile of the design task the expert designers essentially placed a similar amount of emphasis on the same classes of Design Suppositions. Two key questions arose out of the results. First, were the interrelationships of the classes of Design Supposition such that they were always ranked in the same way throughout the design task? Secondly, to what extent was there any disparity between the designers, in terms of their reporting of the different classes of Design Suppositions?

**7.2 Ranked position of the Design Suppositions**

In each quartile the data, was ordered in terms the smallest rank to the largest rank (Table2). The research asked, were the classes of the Design Supposition such
that they were always ranked in the same way throughout the conceptual design task?

Class 5 (reasoning and exploration) and class 9 (external visualisation) were largely constant across the design task. The rankings for Class 2 (emergence), class 3 (constraints), 4 (level of abstraction) and class 8 (construction of representation) did not deviate by more than 10. On the other hand, class 1 (external memory aid), class 6 (resolution) and class 7 (reflection) all showed shifts in focus as the design task evolved through time.

<table>
<thead>
<tr>
<th>Quartile</th>
<th>Sum of the Classes of Design Suppositions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18  20  18.5  14  7  37.5  32.5  34  43.5</td>
</tr>
<tr>
<td>2</td>
<td>29.5 29  21  10.5  5  32  32.5  28.5 38</td>
</tr>
<tr>
<td>3</td>
<td>29.5 26  25.5  15  5  28.5  27.5  30  38</td>
</tr>
<tr>
<td>4</td>
<td>34  29.5  26  11  9  11  40  25.5  39</td>
</tr>
</tbody>
</table>

Table 2 Ranks assigned to the classes of Design Supposition, for the entire design task

7.2.1 The use of sketches as an External Memory Aid.
An analysis of the designers’ discussion of Design Supposition class 1 (external memory aid) showed that, for four designers, the ranking decreased as the conceptual design task progressed. Indicating that as the design task progressed there was a shift of focus away from using visualizations being used as an external memory aid.

7.3 Inter-relationships of Design Suppositions
The research asked are Design Supposition classes 1 (external memory aid) and 6 (Resolution of an attribute of the problem space) inversely related to one another?

In response to the second question, Design Supposition classes 1 and 6 were compared against each other. Figures 4-8 show, for each designer, the data for the use of sketches as an external memory aid and their use of sketches to aid problem resolution. The results showed, that for the designers who exhibited a shift in focus away from the use of sketches as memory aids, the shift coincided with an increased use of sketches to resolve specific attributes of the design. The results indicate that for four of the five designers the classes 1 and 6 seem to be inversely related to one another.

7.2.2 The Use of Visualisations to aid Problem Defining / Resolution. All the designers exhibited a shift in focus with regards to the resolution of specific attributes of the problem space. The nature of the shift is highlighted by the lines in the figure 3. The lines illustrate the relationship between the designers’ retrospective verbalisations of the resolution of an attribute of the problem space, and the development of the design task. For all the designers there was a positive increase in the ranked position of Design Supposition class 6 as the task time increased. Therefore it may be concluded that as the design problem space evolves sketching is used increasingly to aid problem defining / resolution of attributes of the design problem space.
8. Conclusions

The paper has developed a classification-coding schema in order to deal with the relationship between the concepts of the sketch, as an external visualisation, and the protocols that describe the purpose of the visualisations. The taxonomy has been validated by a set of encoders and used to examine five expert architects’ use of visualisations. The approach allows a rigorous and consistent analysis of architectural design activity and the use of visualisations in the early stages of conceptual designing. The research has demonstrated that there are ‘shifts in focus’ with regards to the designers’ use of visualisation to aid the resolution of the design problem space.

The identification of the shifts in focus, in terms of the functional use of visualisations, has implications for future Computer Aided Design tools for early conceptual design. Computational tools proposing to facilitate conceptual design must support the reasoning process facilitated by current methods of visualisation. The results suggest the most successful approach will be one that concurs with the notion of the ‘right tool at the right time’, a notion first suggested by Ellen Do[8]

References


