Studying Designers‘05

Studying Designers'05

Preprints of the
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edited by
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TABLE OF CONTENTS

Preface **vii**

SESSION ONE **1**

Reasoning by reference to past designs 3
C. Eckert, M. Stacey & C.F. Earl

Evocation of new ideas in creative design 21
N. Bonnardel & E. Marmèche

Differentiation: Designers are more than being adept at designing 33
M. Suwa

The capture of design eureka 39
Y.-C. Chiang & M.-H. Wang

SESSION TWO **55**

Ethical aspects of the product design process 57
P. Lloyd, W. van der Hoog & I. van de Poel

Dual protocol analysis based on design information and design process 71
Y. S. Kim, S. T. Jin & H. S. Lee

The nature of creativity in design 87
H. Casakin & S. Kreitler

A cognitive model of the engineering design mind 101
J. S. Elias & S. Dasgupta

SESSION THREE **117**

Visual reasoning in the design process 119
H.-H. Tang & L.H. Tsai

Software authors as designers 129
A. Woodcock

Does sketching off-load visuo-spatial working memory? 145
Z. Bilda & J. S. Gero

A role for external representations in architectural design 161
F. Decortis, S. Safin & P. Leclercq

SESSION FOUR **179**

A diary study in the engineering domain 181
P. J. Wild, C. McMahon, S. Culley,M. Darlington & F. Liu

A framework for experimental laboratory design experiments 197
D. Choulier & E. Pena

Content-based design analysis 213
P. Saariluoma, K. Nevala & M. Karvinen

Entropy measurement of linkography in protocol studies of designing 229
J. WT Kan & J. S. Gero

SESSION FIVE **247**

Individual designing behavior and learning style: Investigation of the design process of interior design students 249
S. Bar-Eli

Usage of methods in student projects 267
S. Schneider & U. Lindemann

Exploring the everyday designer 277
R. Wakkary

Studying outstanding designers 283
N. Cross & B. Lawson

SESSION SIX **289**

Studying design collaboration in virtual environments 291
M. L. Maher, Z. Bilda and F. Gul & D. Marchant

An ethnographically oriented study of designers in a collaborative design project 307
S. Joel, M. Smyth & P. Rodgers

Cognitive studies in similarity assessment 323
J. R. Jupp & J. S. Gero

SESSION SEVEN **333**

Espoused theory and theory-in-use: Denys Lasdun's design credo 335
G. Goldschmidt

Accidental resource 343
A. Heylighen, W. M. Martin,& H. Cavallin

The semiotics of product aesthetics 351
N. Crilly & P. J. Clarkson

Implications of metacognition in design 349
J. Jänsch & H. Birkhofer

Critical points for change 355
P. Parthenios

Modelling technology enhanced learning environments through designers observations 361
M. de Grassi, A. Giretti & M. Mengoni

Exploring the effects of introducing real-time simulation on collaborative urban design in augmented reality 369
S. Attfield, C. Mottram, A. F. G. Schiek, A. Blandford & A. Penn

Architecture design intelligences 375
N. D'Souza

CONTACT AUTHORS EMAIL ADDRESSES **383**

AUTHOR INDEX **385**

PREFACE

The purpose of this workshop is to advance our understanding of designing as an activity, i.e. how professional designers, students in design or even lay-persons create and develop the representation of an artefact that is both new and adapted to a given context.

Studying human designers can be carried out in many ways ranging from experiments in laboratories with individual designers, experiments in laboratories with design teams, to in-situ studies of individuals and teams. The experiments can be concerned with elaborating aspects of the acts of designing or of changing the design environment. The latter is generally concerned with the introduction of various forms of computational and communication technologies. Many of these are represented in the papers in this volume.

This volume presents the preprints of the *International Workshop on Studying Designers'05*.The issues addressed are what are the cognitive processes involved in design activities? Especially, what is the role of past experience and knowledge, and how are they integrated in order to design a new product?

- How can we understand creativity in design?
- What is the role of design representations and visual reasoning in designers' activities?
- What is the role of collaboration in performing design activities?
- What methods are useful for studying designers' activities?
- How can we teach students to become designers?
- What is expertise in design?

The papers were selected from the submissions by two referees.

The financial support of the University of Provence is gratefully acknowledged as is the infrastructure support of the Key Centre of Design Computing and Cognition of the University of Sydney in organizing this workshop. Mercèdes Paulini worked hard to produce a coherently formatted volume.

John Gero and **Nathalie Bonnardel**
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SESSION ONE

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REFERENCES TO PAST DESIGNS

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Abstract. Designing by adaptation is almost invariably a dominant feature of designing, and references to past designs are ubiquitous in design discourse. Object references serve as indices into designers' stocks of design concepts, in which memories for concrete embodiments and exemplars are tightly bound to solution principles. Thinking and talking by reference to past designs serves as a way to reduce the overwhelming complexity of complex design tasks by enabling designers to use parsimonious mental representations to which details can be added as needed. However object references can be ambiguous, and import more of the past design than is intended or may be desirable.

1. Introduction: Designing by adaptation

Designers hardly ever start from scratch, but design by modifying existing products. Complex products such as aircraft or jet engines evolve from generation to generation, often over decades, through the transfer and revision of design elements. This transfer of design elements takes place at different levels of abstraction ranging from general solution principles to details of component manufacture.

There are sound economic reasons for reusing components and subsystems in designs, as well as approaches and solution principles. Reusing parts and tooling makes a new design cheaper. Components that have been tested and certified do not have to be recertified. The closer the new design is to an old design, the easier it is to predict, and reduce the risks of, particular failure modes over the lifecycle of the design. Within the design process, uncertainties and risks vary from high risks associated with innovative parts to low risks associated with parts with similar functional specifications reused from other products. It is easier to plan a design process when innovation is limited to some part of the product, and with other parts adapted to new needs. Design processes themselves also have parts which are adaptations of previous processes especially for similar product parts and subsystems. Again planning is easier when innovative and potentially more risky processes are limited to part of a product or to a particular process activity.

However, the use of existing solutions goes far deeper than product and process characteristics to the way in which designers reason about a new design. Reasoning by similarity and analogy is a central part of human cognition (see for instance Holyoak and Thagard 1995), and designing by analogy enables designers to cope with the otherwise overwhelming complexity of design tasks. Memories and external records of previous designs are primary sources for the elements of new designs. References to them provide concise indices to design knowledge; these indices are easy to communicate in discussions. But as representations of previous designs comprise tight linkages between function, behaviour and structure they also constrain designers in conceptualizing and developing design alternatives.

2. References to past designs are ubiquitous in engineering design

References to existing objects are ubiquitous in design processes and can be used in many different roles. Designers refer to entire objects, parts of them or even groups of objects at once. This section reports on different functions we have identified from several empirical studies but illustrated with examples from one of these, namely diesel engine design for off-road vehicles.

2.1. EMPIRICAL STUDIES

Since 1999 the first author and members of the Engineering Design Centre at Cambridge University have carried out several detailed studies in engineering design companies to understand communication between design teams, planning design processes in industry and the effects of changing parts in existing products (Eckert, Clarkson and Zanker 2004; Eckert and Clarkson 2003). Overall nearly 100 engineers and engineering managers in seven large UK aerospace and automotive companies were interviewed. The interviews were recorded, transcribed and later analyzed by the authors and other researchers for different research questions. Many informal interviews and discussions were held with designers and managers in these companies. In three of the companies several meetings were observed which concentrated on changes to existing products. Although these meetings could not be recorded for reasons of confidentiality, general characteristics of change processes were noted.

This research has included extensive interaction with Perkins Engines, who produce diesel engines for off-road vehicles such as tractors or diggers, and for generator sets. Several members of the first author's team have conducted extended case studies in Perkins with observations to analyze how existing products are changed (Jarratt 2004) and how processes are planned (Flanagan et al. 2005).

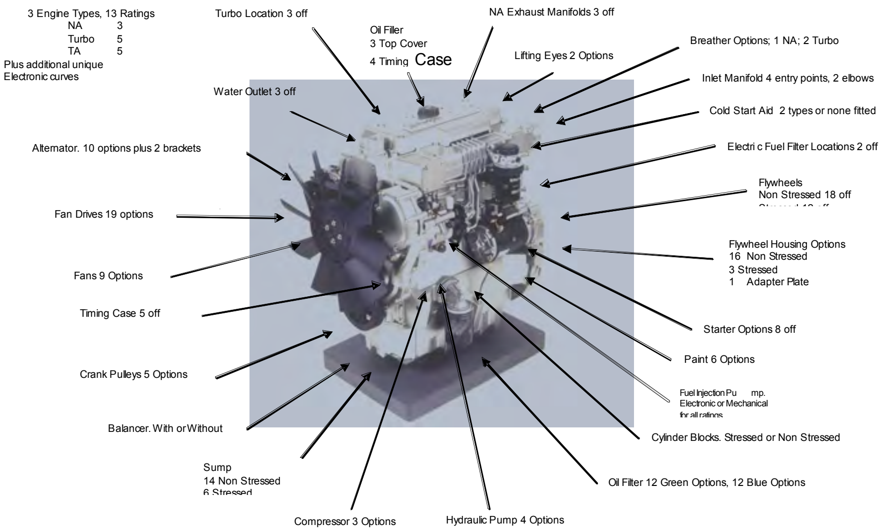

Figure 1: Versions of a diesel engine

Diesel engines were patented in 1898 and are very mature products; they have been refined over many generations of engines but their fundamental solution principles have changed little. Unlike car engines, off-road diesel engines are built to run at 100% of capacity most of the time when they operate, requiring great reliability. Under increasing legislative pressure diesel engines have been developed to produce much cleaner emissions. The off road market requires a range of products to cover the spectrum of power requirements from a few kilowatts to hundreds of kilowatts. Each engine has a large number of different versions to meet the needs of particular customer vehicles, as illustrated in *Figure 1*. The development of a new generation of engines is driven by legislation from several sources, particularly US Environmental Protection Agency and EU directives on emissions. However, new versions are constantly initiated to meet customers' specific requirements, which mainly involve changes to the geometry of engines. Creating customized versions is a key part of the business.

2.2. ROLES OF OBJECT REFERENCES

In all the case studies we have conducted, objects references have been a recurring part of many design discussions as well as interviews. References to previous designs play an important role in all the following activities.

- **Design change**. Existing products are changed to meet new customer needs or to eradicate errors in the product (see Eckert, Clarkson and Zanker 2004). In discussing what should be changed, designers talk with reference to the existing product or its versions, to express solution principles, design details and design behaviour. When a component is changed this often has knock-on effects on other components. The extent of change in terms of which components are affected is often estimated by analogy to other design processes, in which similar changes have been made.

  Object references play a vital part in identifying a suitable starting design for a change. For example when a customer approaches Perkins with requirements for a new engine version, Perkins sales engineers examine whether an existing engine already meets those requirements. This can be a formulaic process, but often depends on remembering specific engines sold in the past. If a new version is required, a change request is raised. A decision is made about which engine is closest to the new engine. This existing engine is taken as a starting point. Particular features are drawn from other engines. A typical description of a new engine can sound like this: "The new engine is pretty similar in dimensions and configuration to the tractor engine we did for customer X, if we do with the fly wheel what we did on the 4 cylinder one for customer Y, ….". As there are far more potential configurations than there are names from them, in fact over 30 000 different ones, a past engine is a convenient shortcut for a combination of options, which could otherwise not be expressed succinctly. The engines don't have names, and they typically get referred to by the customer's name.

  In design change, past objects are used as starting points; as sources of systems and components that can be reused; as sources of solution principles that have been successfully employed; as reference points for any relevant features and as shorthand for experiences in design, manufacturing, service and use.
- **Design process planning**. At the beginning of a design process, tasks need to be identified, gateways defined and resources allocated. While much of this is covered by standard procedures,

design managers need to make judgements about which problems it will be necessary to solve, which parts, processes or solution principles can be reused, and how the skills of the people involved match these tasks (Eckert and Clarkson 2003). The similarity assessments involved in process planning are similar to those in change assessment; however planning is a far more open-ended process. Companies can estimate how much effort is involved designing a particular component. For example Perkins keeps certain components fairly constant, because their redesign would cause significant design effort, while others are much easier to redesign. Projects need to be planned as soon as a concept is accepted, but before the company really knows what innovation will be required for the new product. They usually do this by trying to assess how different the new project will be in terms of product and process from a number of familiar projects. Typically the project manager requests plans from individual team leaders who have worked on a similar part in the past. The team leader assesses the effort involved in designing the part by reasoning about how long similar parts took in the past, whether these can be modified thus speeding up the process, or whether a redesign would take the same length of time as the original part, given the experience of the available team members. Then it is necessary to decide which parts to design anew. Both time estimates and expertise estimates are done with reference to past designs. The project manager then collates the plans, accounts for the conservativeness of personal estimates, and adds a contingency factor to the entire plan. As planning is so dependent on personal experience, individual managers plan in very different ways. In contrast to discussions about changes, people seldom mention the sources of plan elements when they are communicating plans to their colleagues. In interviews managers explained how they plan and make estimates in terms of assessing similarities to previous processes. However, they were much vaguer about the processes of making these references than they were about elements of the designs themselves.

- **Cost estimation**. To select between design alternatives and to make no-go decisions, designers need to estimate the part, manufacturing and service costs. As there are no effective costing tools for early design, these estimates are often made by cost engineering experts based on high level similarities, without any assessment of how detailed properties will affect cost. Throughout the design process compliance with costing targets is assessed continuously on a component level. When designers make changes, they often reason about whether a similar change in the past caused cost problems.

- **Communication of specific design ideas or solutions**. Designers often describe particular detailed solutions with reference to designs in which the solution has been employed. These reference designs can be quite independent of the starting points for design changes. They are selected for very specific purposes. For example the Perkins engineers might use a competitors' engine to express particular design ideas. Object references in communication can be opportunistic and personal. Less so in Perkins, but in the aerospace companies we worked with, many engineers were aircraft enthusiasts and would express design features with reference to historic aircraft that had used a particular solution principle. Solutions seem to be indexed by references to single examples – "we did the …. as we did for the Italians" – making the conversations almost impenetrable for outsiders (see Eckert and Stacey 2000; Eckert, Stacey and Earl 2003). The references can contain a rich message expressed concisely. Objects that combine features provide a convenient way to express or refer to these groups of features. However the scope of these references can be ambiguous. The comparison points through which a design is communicated do not have to be the same as those used in the generation of the design, because they might have been created later or the similarities might have been recognised later. A reference to a completed product is not only a concise way of expressing ideas, it also adds a degree of credibility to a suggested solution, because it derives from something that already works.
- **Generation of solution ideas**. When designers look for new ideas for entire designs or particular aspects of a design, they review their own past designs and the designs of their competitors. For the mature products whose development processes we study, idea generation happens at several points in the process. At the very beginning a new product is devised by a very small team of people. Perkins has a chief conceptual designer, who has been working in the company for several decades. He is familiar with all the past products, and comments that when thinking about aspects of a new engine he mentally surveys the designs and configurations of past engines to draw ideas from them. He also assesses the impact of changes that need to be made to create the new engines; this is a systematic procedure guided by remembering where problems have occurred in the past. He also explained that his main way of reasoning about product trade-offs is by thinking about how well engines that incorporated a similar trade-off decision have worked in the past.

Idea generation also occurs at a more local and detailed level later in the design process especially when resolving problems. Almost paradoxically a lot of innovation happens late in design processes or even during changes once a product has gone into production. This happens partly to avoid changes to frozen parts. Designers often comment that when they are looking for solutions to specific problems they need to know about past designs and where the company has already solved this problem. In Perkins, which has produced hundreds of engines, this is a serious issue. These comments were often made in Perkins apropos of experts retiring. For example a cost engineer, whom we spoke to shortly before he left the company after over 40 years with Perkins, commented that he had a personal filing cabinet full of past cost-saving solutions, which he would remember and get out in particular situations.

Increasingly companies look to other industry sectors to see how they have solved similar problems. For example aerospace designers look at car designs and conceptualize the solutions they find in terms of the cars in which they have occurred. Up to now we have not encountered systematic procedures for looking at other industries, but have heard many causal references to solutions in other industry sectors.

- **Corroboration of design ideas**. When designers work out several solution alternatives for a particular part or system, they often look at competitor designs, on the assumption that if their competitors have employed a particular standard solution concept for this particular problem, they must have tested it. This use of references to other designs is similar to the communication of provisional ideas by reference, but occurs at a different point in the process, after ideas have been partially developed; and with a greater degree of reflection. When object references in communication are thought of on the spur of the moment, references for corroboration are carefully thought through. For example Perkins, when considering a new configuration for some struts, considered either using one large one or several small ones. When they realized that one of their competitors had employed a multi-strut version they opted for it as well.
- **Evaluation of solutions.** Once design solutions have been generated, specific object references again play an important role in corroborating the new design. Now it is possible to assess the similarity of the new but yet untested design and an existing reference design with known long term performance characteristics. In a right-first-time design culture this is increasingly important, as designers are only allowed to use physical testing to verify a design,

rather than to try out a design or learn about its performance. Perkins is developing a "confidence measure" (Flanagan et al 2005) which assesses how sure they are that a new design component will work. This is computed from a combination of particular evaluations and similarity to existing components. If a component is very similar, they have greater confidence and need less testing to be sure. This does not replace the testing necessary to assure safety, but can guide the design effort in an organization.

In summary designers employ object references throughout the design process; however references are most frequent and important at the beginning and the end. Designers use object references to come up with ideas, assess changes and plan processes at the beginning. Later they use different object references to corroborate design ideas and evaluate solutions.

2.3. SUPPORT FOR DESIGNING WITH OBJECT REFERENCES

Tools and methods for supporting designers in using past designs and solution principles have focused on idea generation and design synthesis particularly in the early stages of design. The importance of designing by adaptation is well-recognised by design theorists, notably Gero (1990), as well as practitioners (see Eckert, Stacey and Clarkson 2000). And case-based reasoning techniques (see Kolodner 1993) have been widely used in research on design synthesis (see Voss, Bartsch-Spörl and Oxman 1996). Case-based reasoning systems select a reference design and modify it to meet new requirements. This parallels the role of object references in change. Generative and grammatical techniques comprise sets of generative rules that are extracted from a canon of reference designs.

Other researchers have recognized the more opportunistic nature of object references in design generation and the potential value of supporting the retrieval of previous designs. For example Büscher et al (2001) have developed a computer tool that catalogues reference designs for the communication of ideas in landscape design; Goldschmidt (1995, 1998) discusses the role of visual databases in using precedents and references in architectural design.

Curiously, although there is a large body of literature on design process planning, little attention has been paid to the adaptation of existing plans to new designs, although this is a well-known approach in manufacturing process planning. The tools that come closest to supporting design process planning by object reference are attempts to develop process modelling building blocks (Bichlmaier 2000; Wynn, Eckert and Clarkson, 2005).

3. Design thinking requires complexity management

Human beings are severely limited in the complexity of the things they can keep in mind at one time (see Cowan 2001), and typical engineering products that designing engineers create are far too complicated to comprehend fully. Designers employ a variety of strategies for coping with this complexity and wealth of information.

3.1. THINKING WITH HIERARCHIES OF COMPONENTS

As Simon (1996) pointed out, designed complex systems are organized as ‘nearly decomposable’ hierarchical structures with components whose interactions are much simpler than their internal workings, so that it is feasible to understand each element in terms of its behaviour and the interactions of its subcomponents. In some design processes, notably in software, choosing appropriate components to achieve clear and simple decompositions is an important part of designing; reorganizing component hierarchies is an important part of object-oriented software development (see Fowler 1999).

3.2. THINKING WITH ABSTRACTIONS

An alternative, and complementary, approach to reducing the complexity of the thinking designers need to do is to consider different *aspects* of a design separately. For instance Hoover, Rinderle and Finger (1991) observed designers employing different abstractions and corresponding graphic representations to perform analyses of different aspects of their designs. However simplifying by abstracting away from concrete embodiments of design ideas is difficult. Many teachers of engineering design have advocated methods involving thinking abstractly about the functions that products and their subsystems should perform, such as Suh’s (2001) axiomatic design method, Andreasen’s (1991) theory of domains, and the functional analysis that is part of Pahl and Beitz’ (1995) method. These methods are widely taught, but in practice most engineers struggle to think about designs in the abstract with no physical embodiment in mind. Nam Suh has commented (personal communication) that some engineers taking industrial training courses on axiomatic design have great difficulty thinking in functional terms. Other methods for designing in abstract functional terms make the mental operations they require easier by constraining the abstractions they require. TRIZ (see Savransky 2000) is a method for identifying appropriate solution principles for engineering problems based on the analysis of numerous patented designs; it works by abstracting out the essential functional transformations required by a problem and mapping these to a set of standard solution principles. It is usually used in conceptual design, but can also be applied in the development of design ideas in later stages of the process. It provides a systematic method for finding and using analogies to past designs (stored in a relatively abstract form). C&CM is a method for analyzing and modifying existing designs, based on assigning functions to working surface pairs of specific designs, thus providing functions with a specific location on an object (see Albers, Ohmer and Eckert 2004). C&CM requires abstraction to a functional view but keeps the functional thinking connected to physical embodiments and localized to interactions between individual components.

Mechanical engineers typically think visually about designs, often with mental images of designs that may be more specific than is strictly necessary for the current task. We have found that when designers are prompted to list the functions that their product must carry out, they often list the functions that particular components need to carry out, once they go beneath the top level functions (see Jarratt 2004 for an example of a group session to elicit product functionality). In many other situations, designers talk about functions by immediately mentioning the components that carry them out.

However, engineers switch between different levels of abstraction, and there are differences between different kinds of engineers that depend on the tasks they carry out. Anecdotal evidence from 20 interviews with helicopter designers (Eckert, Clarkson and Zanker 2004) revealed an interesting difference in how designers thought through their design problems. All the designers were asked about their mental representations, and a clear pattern emerged. The apprentice-trained engineers, who were team leaders for key mechanical components, claimed that they visualized design problems in terms of concrete three dimensional solutions, based on past designs that they knew. By contrast several of the design analysts, who were university-trained, explained that they reasoned about design problems in terms of correlation relationships between key parameters and properties of the components and systems they analyse. Similar distinctions seemed to emerge among the Perkins engineers but they were not systematically questioned on the point.

3.3. THINKING WITH DESIGN CHUNKS

Designers cope with the limited capacity of working memory when reasoning about more complex designs and situations than they can keep in their entirety in focal attention, by being able to reconstruct and retrieve elements of complex mental representations as they switch their attention (see Cowan 2001 for a discussion of the capacity of working memory).

Designers working on their own or in meetings commonly use sketches and other graphic representations of design information, that can serve as cues for the rapid recollection or reconstruction of information when it is needed (see Purcell and Gero 1998, for a review of research on sketching in design). And sketches often have an important role in the collaborative development of designs in meetings (see for instance Minneman 1991). The explicit information content of the representations created in the course of designing is only the tip of the iceberg: it provides cues triggering the recall of designers' knowledge about the types of design elements signalled by the representations, and this knowledge guides interpretation of the representations. Similarly interpreting CAD models and schematic diagrams is a learned skill involving the activation of knowledge in memory.

In our studies of how engineering designers work, we have found that designers activate chunks of design knowledge by verbal references to individual past designs and to narrowly and concretely defined classes of designs. We have also observed that this is an essential part of knitwear designers' design thinking and discourse (Eckert and Stacey 2000).

The chunks of design that designers recall are often highly structured; while only parts or aspects of a design may be held in working memory at one time, they activate memories for other parts (see Anderson 1983). Memories for designs include concrete details of how functions are embodied in solution principles and how solution principles are implemented with specific types of components, and how these are configured. Memories of structural elements are linked to memories of behaviours and problems such as vibration, as well as functions. Depending on how well they remember them, designers can imagine designs employing elements of past designs, that have more structure and detail implied by the relationship to the past design than the designers can keep in working memory. This additional information can be recalled as required and compared to the needs of the present situation. Thus designing by adaptation enables designers to reason about complex designs more easily. Rather than deduce consequences they recall the implications of previous design decisions.

How much of the remembering of past designs is recall and how much creation is not obvious; as evidence from mental imagery research indicates that details of visuospatial representations are only generated when attention is directed to them (Kosslyn 1980), and extensive psychological evidence indicates that memory recall is heavily dependent on memory for categories and causal relationships (see Schank and Abelson 1977). Oxman (1990) and Kulinski and Gero (2001) argue that constructive memory processes play an important role in design thinking.

4. Adapted designs can bring more than is intended

The consequence of references to existing designs is that when designs are created by modifying remembered or referred-to designs, or adopting elements of them, more is imported into the new design than just a solution principle for the subproblem that the designer is focusing on. The imported design element is imagined as a concrete embodiment, modified to fit the new context – to be coherent with the rest of the design. It also carries with it assumptions about its physical properties, materials, manufacturing process and context of use. Some of these assumptions may be necessary for the design to work; others may be invalid in the context of the new design.

When designers want to think abstractly about solution principles, the abstractions trigger memories for examples. Designers find it difficult to break away from the design elements and solutions to problems they remember, to imagine something different, even when they *know* they are inappropriate – this is known as *fixation* (see Jansson and Smith 1991; Purcell and Gero 1996). Designers may not question particular aspects of a design that have always been done in a particular way. These assumptions (part of the designers' *mental set*) can apply to features of existing designs that are inherited. Designers can also fixate on a particular feature of a new design from the beginning and never modify it. Memories for designs may not include the rationales for design decisions – or the designers may never have known them – but they may fear to change design elements in case they will no longer work correctly; unimportant features may simply be carried over.

The ability to make use of object references is closely linked to expertise (see Lawson 2004). However with increasing expertise designers make more use of more abstract schemata in conceptualizing new designs (Ball, Ormerod and Morley 2004); Lawson (2004) presents an example of architects using shorthand phrases to mention shared schemata. Experts have seen more designs and have more experience with design processes; they have a greater and more subtle understanding of visual and behavioural patterns, and therefore can spot resemblances to other designs – and ways they are relevant – that a novice might not see. Experts also know which parts of a product can be modified easily and which not, and therefore prioritise design decisions accordingly. However the development of decision strategies based on past unsuccessful or difficult experiences with ideas or solutions may sometimes limit their creative scope compared to novices. Potential solutions may be filtered out for invalid reasons (see Eckert, Stacey and Wiley 1999). The development of detailed memories for a sufficiently wide range of previous designs, as well as categories of solution principles, is an important part of education in architecture, and a fundamental part of the transition from a design novice to a design expert. For example novice jet engine designers learn about the theoretical and engineering development of turbojets in order to reason and converse about these engines and their parts.

5. Object references are chancy and potentially ambiguous

Objects references used to communicate design ideas to others can be ambiguous, because it may not be clear whether designers wish to reuse the entire reference object or only one part or aspect of it. As we have pointed out elsewhere (Eckert, Stacey and Earl 2003) this can not only be a source of hidden mismatches between different designers' understanding or views of the design, but also the genesis of creative ideas as object references suggest new solutions.

Reasoning by object reference can be a powerful way of selecting and working with large and coherent solution chunks, but can also be a chancy and unsystematic process. How particular previous designs are retrieved from memory may depend on what aspects of the design problem trigger recall, or are in mind when the designer searches for a related design; problem framing is an essential part of design thinking (Schön 1988; see Cross 2004). Research on the construction of analogies indicates that analogous situations are retrieved according to how similar they are to the aspects of the current situation that people focus on, and that this depends on how they have constructed a mental representation of the analogous situation (Dunbar 2001). If designers think about adapting one previous design, the features of that design may over-constrain how they think about particular parts of the new design, when a component or solution principle from a different design might be more appropriate. For example project managers complain bitterly that designers forget that they have already generated a component, employed in another product, that would meet the exact requirements for the current design problem. Designers and their companies sometimes put considerable effort into redeveloping something that already exists in another product. While this can be a sign of bad information management, it can also be a design shortcoming with designers failing to identify what designs and design elements might be relevant.

6. Designing by adaptation is the creation of conceptual coherence

We have observed engineering designers employing analogies to past designs for a variety of purposes. Not only is adaptation an essential aspect of designing, but comparisons and adaptations of previous designs are important for communicating ideas and planning processes. References to past designs are ubiquitous in design discourse. The common thread is the search for as close a match as possible to a current problem that specifies both some of the elements of a solution, and the constraints the solution has to meet. Dunbar's (1997) observations of molecular biologists and immunologists at work reveal a similar pattern: scientific reasoning in conversations and meetings makes frequent use of analogies, almost always to very similar situations. Dunbar found that analogies served three major goals: formulating theories, designing experiments, and giving explanations to other scientists; analogies are frequently used when unexpected findings occur. Dunbar discovered that the scientists he observed have little memory of the reasoning processes that have gone into a particular scientific finding, and in particular the analogies they employed; the analogies appeared to serve as scaffolding, discarded as soon as they achieve their purpose. Dunbar concluded from this that it is necessary to treat retrospective reports of reasoning processes with caution.

What the different uses of object references in designing also have in common is that they employ universal psychological mechanisms for developing mental representations of situations by aligning different elements to achieve conceptual coherence (Thagard 1989; Thagard and Verbeurgt 1998; Johnson-Laird, Girotto and Legrenzi 2004). The design synthesis actions involved in the development of new designs employ the building blocks provided by the designer's memories and current perceptions; these include mental representations of past designs as well as representations of categories and solution principles, plus representations of requirements and constraints. The elements, requirements and constraints in focal awareness exert the strongest influence, but elements activated in memory by related recent experience are *primed* for easier recall (see Anderson 1983). These elements are modified and combined into a mutually consistent structure in the rapid construction of mental models of modified designs through a process of constraint satisfaction (see Johnson-Laird 1983; Johnson-Laird, Girotto and Legrenzi 2004).

This process depends on the identification of significant similarities between the current situation and some past design or more abstract schema. This depends both on the resemblances between elements and on the structural relationships between elements; the development of a coherent mapping is crucial (see Gentner 1983; Gentner and Markman 1997). In experiments on similarity judgements, similarities between individual features are more powerful when similar items are recalled from memory; but broader structural similarities are more powerful when visually available items are compared (Gentner, Ratterman and Forbus 1993). But people readily recall structural analogies from memory when searching for particular structural relationships, and when their memories for the to-be-recalled analogies include these relationships (Dunbar 2001).

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FAVOURING CREATIVITY IN DESIGN PROJECTS

Challenges and Findings of Experimental Studies

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Abstract. In order to better understand and favor creativity in design projects, we conducted experimental studies focused on the designers' evocation processes of creative ideas. The first study aimed at determining whether creative ideas can be enhanced by the presentation of external sources of inspiration, pertaining or not to the same semantic domain than the object to design. Results show that for experienced designers, but not for novices, the presentation of sources of inspiration semantically far from the object to design favors evocation processes. The second study focused on the affects, positive or negative, conveyed by the suggested sources of inspiration. Results show that positive sources lead to the evocation of more creative ideas than the negative ones. Finally, the third study, focused on judgments of the potential usefulness of various sources of inspiration, shows important differences between novices and experienced designers. Experienced designers consider that all the suggested sources, near or far from the object to design, may be useful in the design process. They adopt diverse points of view about the sources, and try to integrate the evoked aspects taking into account constraints expressed in the design problem. These results lead us to define operational objectives in order to favor creativity in design projects, especially for novice designers.

1. Creativity and Design

Creative activities, such as non routine design, can be characterised as a special form of problem solving (see, for instance, Matlin, 2001). A main characteristic of these activities is that the initial state is ill defined (Reitman, 1964; Eastman, 1969; Simon, 1973): designers have, initially, only an incomplete and imprecise mental representation of the design to be performed. The designers' mental representation evolves as the problem solving progresses. Thus, the design problem-solving has been described as resulting from a *co-evolution of problem and solution spaces* (Dorst and Cross, 2001) and as based on an iterative dialectic between *problem-framing and problem-solving* (Rittel and Webber, 1984; Simon, 1995). In this framework, our general objective is to contribute to a better understanding of how designers develop new ideas for creating a specified object. Indeed, a challenge for designers is to introduce creativity in the design projects they work on and to minimise the tendency to repeat familiar design features.

Therefore, we are going to focus on designers' cognitive processes, in line with cognitive-components approaches of creativity (see, for instance, Ward, Smith, and Vaid, 1997). Based on both observations in professional design situations (see, for instance, Bonnardel, 1992; Dorst, 1997) and experimental studies involving real design problem-solving activities (Bonnardel, 2000; Bonnardel and Marmèche, 2004; Détienne, 2001), we argue that, at least, two main cognitive mechanisms interact during creative design problem-solving: analogy-making and the management of constraints. Analogy-making could open up or restrict the "space of research" of new ideas, depending on the nature of the sources of inspiration that are evoked for solving the problem at hand. Constraints would dynamically orient the designers' reasoning towards appropriate decision-making and choices of design options.

In line with this description, creativity has been characterized as resulting from the activation and re-combination in a new way of previous knowledge elements in order to generate new properties based on the previous ones (Wilkenfeld and Ward, 2001). Moreover, according to Ward's structured imagination framework, people who are engaged in generative cognitive activities have to extend the boundaries of a semantic domain by mentally crafting novel instances of the concept. However, experimental results show that people have a strong tendency to rely on exemplars (Jansson and Smith, 1991), even when they have been instructed to be as creative as possible. In fact, the more the participants can move away from the first evoked sources, the more they are creative and original (Ward, Patterson, Sifonis, Dodds, and Saunders, 2002). It seems, therefore, that the most successful uses of analogies may depend on the capacity to move beyond initially retrieved information to better or more refined exemplars, interpretations and source analogues.

2. Research Goals and Design Problem at Hand

In order to deepen such topics, we conducted experimental studies that aim at determining (1) whether designers' creative ideas can be enhanced by the presentation of external examples or sources of inspiration, and (2) to what extent designers consider potential sources as useful for solving a specific design problem.

Since previous results in cognitive psychology tend to show that expertise in a domain leads to a freeze in the research space (experts being used to deal with the same usual problems), we decided to analyze the impact of the designers' level of expertise on the evocation of new ideas. In contrast to other areas of expertise, in creative design, we argue that such a "freezing" effect should not be observed, since designers have always to search for creative ideas. Thus, we hypothesize that:

- experienced designers can extend more their space of research of new ideas than novices;
- experienced designers will be more able than novices to benefit from the suggestion of sources of inspiration;
- experienced designers will consider suggested sources of inspiration as more relevant for solving the problem at hand than novices and they will be more inclined to adopt various points of view about these sources.

The experimental studies are built around the same design problem, which aims at designing a new seat for a cyber-café. Participants are provided with a set of requirements, which specifies that the seat should respect specific constraints:

- to have a contemporary design in order to be attractive for young customers,
- to allow the users to have a good sitting position holding the back upright, to put their knees on a support intended to this function, and to relax by offering them the possibility to rock.

In the first series of experiments, participants are asked to solve this design problem either freely or in guided conditions. In the guided conditions, depending on the experiment, participants are provided with intra- or interdomain sources of inspiration (*i.e.* that belong or not to the same conceptual domain as the object to be designed), or with sources conveying a positive or a negative affect. In the second type of experiment, participants have to judge and comment on the sources of inspirations evoked by participants in the previous experiments.

3. Does guided problem-solving with intra- or interdomain sources favor the evocation process?

3.1. METHOD

The first study was conducted with 75 participants, experienced designers *vs* novices. They had to solve the design problem presented above while thinking aloud.

Their verbalizations were transcribed and analyzed separately by two judges. Then, the obtained results were compared and we reached a good degree of agreement. The data analysis was especially focused on the number and nature of new sources evoked by the participants.

Depending on the experimental group they were assigned to, participants had to solve the problem "freely" or they were provided with two potential sources of inspiration ("guided" conditions). In this last case, the suggested sources could be either intra- or interdomain:

- Suggested intradomain sources pertain to the "seat" category, which is the category the object to be designed (*i.e.,* the seat for the cyber-café) belongs to; they consist of an office chair and a rocking chair.
- Suggested interdomain sources do not belong to the category of the object to be designed and they consist of a climbing position and a logo.

In addition, we manipulated the format of presentation of the suggested sources. They were either presented as verbal labels (*i.e.*, names of the objects-sources of inspiration) or as graphical representations of the same objects-sources of inspiration, Table 1.

3.2. RESULTS

The format of presentation did not allow us to find significant effects (only tendencies were observed). Thus, results of this first study are focused on the effects of the nature (intra- *vs* interdomain) of the suggested sources of inspiration.

3.2.1 Quantitative results

A first result observed both in free and guided conditions is that experienced designers evoke significantly more new sources of inspiration than novices.

The quantitative results obtained with *novice designers* show that, by comparison with the free condition, the suggestion of intra-domain sources of inspiration tends to favor the evocation of new intra-domain sources of inspiration whereas the suggestion of inter-domain sources does not seem to impact on novices' evocation processes, Table 2.

In contrast, for experienced designers, we observe a limitation of the evocation of sources when they are provided with intra-domain sources, by comparison with the free condition (see Table 3). This result is in line with the one obtained by Jansson and Smith (1991) about the effect of intradomain sources presented as examples.

However, our study shows also that an opposite effect is obtained when experienced designers are provided with interdomain sources. In this case, these sources highly facilitate the evocation of new interdomain sources.

TABLE 1: Suggested sources of inspiration

Nature of sources / **Format of presentation**	**Intradomain**	**Interdomain**
Graphical representations	 	 
Verbal labels	OFFICE CHAIR ROCKING-CHAIR	CLIMBING POSITION **LOGO**

TABLE 2. Mean numbers and nature of sources evoked by <u>novices</u> in the free and guided conditions (intra- or interdomain sources of inspiration)

Experimental conditions / Nature of evoked sources	Free condition	Guided conditions Intradomain	Guided conditions Interdomain
Intradomain	1.8	2.7	1.3
Interdomain	1.1	0.8	1.6
Total	2.9	3.5	2.9

TABLE 3. Number and nature of sources evoked by experienced designers in the free and guided conditions (intra- or interdomain sources of inspiration)

Experimental conditions Nature of evoked sources	Free condition	Guided conditions Intradomain	 Interdomain
Intradomain	3.4	1.0	2.2
Interdomain	3.0	2.8	8.3
Total	6.4	3.8	10.5

3.2.2 Qualitative results

Qualitative results, *i.e.* related to the nature of evoked sources, show that, in the free condition, both experienced and novice designers spontaneously evoked mainly intradomain sources (see Tables 2 and 3). Such sources consist, for instance, in an *automatic photo booth chair*, a *dental office chair* or a *camping chair.*

However, we observe that, in contrast to novices, experienced designers can avoid such a spontaneous behavior when they are provided with potential sources of inspiration: in guided conditions, they evoke mainly interdomain sources, whatever the nature (intra- or interdomain) of the suggested sources. These interdomain sources consist, for instance, in a *wave,* a "*Prie-Dieu*"*,* a *nest* or a *weightlessness position.*

4. Do positive or negative affects conveyed by sources of inspiration favor the evocation process?

4.1. METHOD

This second study, in collaboration with Michael Saïd, was conducted with 56 participants (experienced designers *vs* novices). It aims at determining whether graphical representations conveying a positive or a negative affect[1] could influence the evocation of new sources of inspiration by designers.

In the previous study, the graphical representations suggested to participants did not aim at conveying any specific affect. In line with research showing relationships between emotions and creativity (see, for instance, Lubart and Getz, 1997), we argue that the affect, positive or negative, conveying by graphical representations could influence and, possibly stimulate, the evocation of creative ideas.

Towards this end, in this second study, we created a number of graphical representations in order to convey positive or, on the contrary, negative affects. For example, one person was placed on the office chair and had to

1 The notion of "affect" is related to the one of "emotion" but, contrary to emotions that are experimentally induced to participants, affects do not necessarily lead to participants' physiological changes.

express positive (e.g., joy) or negative (e.g., extreme severity) feelings. These graphical representations were tested during a pre-study: 12 judges assessed on a scale whether these representations conveyed such affects. Based on the results we obtained, we selected 8 representations that were judged consensually as conveying either a positive or a negative affect. For instance, for the intradomain source consisting in the office-chair, two images of this object were chosen for conveying, through the addition of a person, either a positive or a negative affect (see Figure 1 for the image with a positive affect). In the same way, for the interdomain source consisting in the logo, two images were chosen for conveying, through the addition of a symbolic object, either a positive or a negative affect (see Figure 1 for the image with a positive affect).

The selected graphical representations were then presented to participants in this second study as potential sources of inspiration for solving the design problem at hand (*i.e.* to design the seat for the cyber-café), while thinking aloud. Depending on the experimental condition, participants, experienced or novices, were provided with 2 intra- or 2 interdomain sources of inspiration conveying either a positive or a negative affect.

Figure 1: Images of the office-chair and of the logo conveying a positive affect.

4.2. RESULTS

The data analyses were conducted with regard to:

(1) the designers' level of expertise, novices or experienced participants;
(2) the kind of suggested sources, intra- or interdomain
(3) the kind of affect conveyed by the sources, negative or positive

We analyzed the number of sources, intra- or interdomain, evoked by the participants of the different experimental groups (see Table 4 and 5)

TABLE 4. Mean numbers and nature of sources evoked by <u>novices</u> depending upon the experimental conditions: intra- or interdomain sources are suggested, conveying either a positive or a negative affect

Suggested Sources	Positive Affect **Evoked sources** Intradomain	Interdomain	Negative Affect **Evoked sources** Intradomain	Interdomain
Intradomain	3,2	1,7	1,25	0,5
Interdomain	1,7	1,5	1,25	0,5
Means	2,5	1,6	1,25	0,5

As in the first experimental study, novices mainly evoked intradomain sources, whatever the experimental condition, whereas experienced designers mainly evoked interdomain sources. Interestingly, a significant effect of the kind of affect conveyed by the suggested sources is observed. Positive sources favour the evocation processes, as well for novices than for experienced designers.

TABLE 5. Mean numbers and nature of sources evoked by <u>experienced designers</u> depending upon the experimental conditions: intra- or interdomain sources are suggested, conveying either a positive or a negative affect

Suggested Sources	Positive Affect **Evoked sources** Intradomain	Interdomain	Negative Affect **Evoked sources** Intradomain	Interdomain
Intradomain	1	2	1	3,3
Interdomain	1	8	1,7	2,3
Means	1	5	1,3	2,8

5. How is the usefulness of potential sources of inspiration assessed with regard to the object to design?

5.1. METHOD

This third study was performed with 27 participants (experienced designers *vs* novices).

After a reading of the design problem presented above, the participants were provided with a set of 18 source-objects, presented as a list of names of objects. This list was based on objects evoked in the first study by designers while solving the problem at hand. It was composed of intradomain sources (e.g., an *automatic photo booth chair*, a *dental office chair*, a *camping chair…*) and of interdomain sources (e.g., a *wave,* a "*Prie-Dieu*"*,* a *nest…*).

Participants were successively involved in two experimental phases:

- in the first phase, they had to select and comment, for each source, which aspects could be useful for designing the cyber-café seat ;
- in the second phase, the whole set of source-objects was presented as a list and the participants had to assess the usefulness of each source-object of inspiration using a scale in five points.

5.2. RESULTS

The results we obtained in this experiment show important differences according to the participants' level of expertise in design, in the two phases.

5.2.1. Results of the first phase

We observed that novices select significantly fewer aspects about the different sources of inspiration than experienced participants: in mean, respectively, 1.38 *vs.* 2.29 aspects.

Moreover, we analysed the kind of aspects expressed by the participants and distinguished 5 categories of aspects:

- Functional aspects, referring to the use of the object; for instance, a participant pointed out that "the seat of an automatic photo booth allows the user to adjust the height of the seat";
- Structural aspects, including a description of parts of the object; for instance, about a bicycle, a participant proposes "to keep the pedals in order to create a foot-rest";
- Affective aspects, reflecting sensations or feelings produced by the object; for instance, about a nest, a participant considered it as "warm" and another one as "bringing a feeling of protection";
- Aesthetic aspects; for instance, about an office-chair, a participant evoked its "modern look";
- Other aspects, which are too much imprecise in order to be allocated to a specific category; for instance, aspects such as "ergonomic" or "rational".

Three judges independently categorized the various aspects expressed by the participants.

The results we obtained show that novices mainly focus on functional similarities between the given source of inspiration and the target-object whereas experienced designers are more inclined to also consider structural aspects, which traduce the adoption of more points of view by experienced designers than by novices.

Moreover, we observed that affective aspects are mainly evoked for interdomain sources, whatever the designers' level of expertise. Only few aesthetic and "other" aspects are evoked by the participants.

5.2.2. Results of the second phase

Concerning the second evaluative phase, whatever the nature of the sources, experienced designers assigned a significantly higher score of usefulness to the various suggested sources than novices (respectively, 3.15 *vs.* 2.6).

In addition, novices assigned a significantly higher score to intradomain sources than to interdomain sources (respectively, 3 *vs.* 2.4). On the contrary, no significant effect was observed for experienced designers (respectively 3.2 *vs.* 3.1).

6. Towards supporting designers

Taken together the results of the three experimental studies show that experienced designers have acquired a particular skill consisting of a stronger fluency in the use of analogical reasoning than novices. Experienced designers can escape from the suggested sources of inspiration, to open up their space of search. They can adopt various points of view about the diverse suggested sources, moving from functional aspects to structural ones, or even affective or aesthetic ones. In addition, they try to keep in mind, more than novice designers, the constraints specified or induced by the design problem at hand. Moreover, when experienced designers have to evaluate the potential usefulness of different kinds of sources of inspiration, they estimate that all sources, intra- or interdomain, may be useful to design a creative object. Finally, for all designers, either novice or experienced designers, it appears that positive affects conveyed by potential sources of inspiration favour the production of new creative ideas.

Therefore, a concrete objective is to support designers, especially novice designers, in developing more powerful evocation processes.

Results of the experimental studies we presented, showed an impact of the designers' level of expertise on evocation processes they develop. At least, three operational objectives can be derived from these findings:

1. To support designers, especially novice ones, in taking advantage of interdomain sources and realize the heuristic power of taking into account interdomain sources.
2. To support them in adopting various points of views about sources, whether they are intra- or interdomain, and not only functional ones, which are the most spontaneously evoked, but also structural, aesthetic, affective....

3. To support them in relying the evoked sources of inspiration to the constraints of the design problem at hand.

Such objectives could be reached, at least partially, through pedagogical actions during design education (Casakin and Goldschmidt, 1999) or through specific creativity training groups (Dewulf and Baillie, 1999). In addition, the use of computational systems, such as the ones developed by Nakakoji, Yamamoto and Ohira (2000), could be particularly useful for providing designers with large database consisting of a lot of pictures or words potentially relevant for creative design tasks.

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JS Gero and N Bonnardel (eds), *Studying Designers'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 33-38

DIFFERENTIATION: DESIGNERS ARE MORE THAN BEING GOOD AT DESIGNING

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Abstract. Studying designers provides insight into not just their ability in design but rather more general issues about expertise, such as what experts are and through what processes they have become what they are now. The present paper, based on the findings from my previous work, provides new discussions about the significance of studying designers from the cognitive science perspective. The central claim is that the ability of *differentiation*, i.e. having keen eyes to respond to variables in the surrounding world that were not evident earlier, is what expert designers differ from novices in, and that this ability is the most requisite in general learning.

1. Expertise-as-differentiation View

The notion of *differentiation* was first advocated by ecological psychologists. To quote Gibson and Gibson (1955), "perceptual learning, then, consists of responding to variables of physical stimulation not previously responded to" (p. 34). This means that experts are able to differentiate and perceive some variables in their body and the surrounding world that would be meaningless to novices. For example, a sommelier is able to differentiately perceive many varieties of subtle tastes of wine, e.g. various types of bitterness.

The expertise-as-differentiation view was not necessarily actively discussed in the mainstream of cognitive science and artificial intelligence. There has been a long history in studies on chunks; expertise was explicated by chunking behavior (e.g. Chase and Simon, 1973). The notion of chunks, however, has a stress on mental structuring of already heeded variables, but not necessarily on differentiation of new variables. Although schema-based learning theory by Rumelhart and Norman (1978) advocated three significant phases of learning, "accretion", "tuning" and "restructuring", it has no explicit mention about differentiation, either. Accretion is to absorb information from new situations in light of a schema the person already possesses, and hence does not involve discovering new variables. Neither the process of restructuring nor of tuning has connotation of differentiation.

In recent years research focus in the studies on learning in cognitive science has shifted from mere conceptual expertise, i.e. knowledge and strategies describable conceptually, onto embodied expertise, i.e. knowledge and skills that are embedded in the relationship between body and the surrounding environment. In other words, how body is involved in expertise has become the central research issue. Here I want to claim that the expertise-as-differentiation view is indispensable in that pursuit. Why? The answer is the following. In general it is not easy for a person to perceive how her own body is involved in learning, i.e. how it moves, what it perceives from the surrounding world, and how those movements and perception are coordinated into a skillful performance. This means that embodied expertise involves many implicit variables concerning the body and the surrounding world. Admitting that becoming an expert involves restructuring relationships between the body and its surrounding world, it is natural to suppose that becoming able to differentiately perceive new variables is central to acquiring embodied expertise. One promising way of research on embodied expertise is a longitudinal study of a dynamic process of a novice's gradually becoming aware of unheeded variables in her body and the surrounding world and creating new coordination between body and the world. The expertise-as-differentiation view is the basis for that research.

2. Reading off from design sketches is an act of differentiation

Design is a treasure box for that research issue. Studying designers from the viewpoint of differentiation is expected to demystify and reveal many hidden processes of learning. My previous work on expert-novice differences in sketching and perception from sketches has convinced me of that idea. Why do designers draw sketches in the early design phase? That is a question that many design tutors and theorists like Schon (1983) have asked. Sketches are not just a record of generated ideas but also a stimulus for new ones. Just because expert designers are capable of reading off new features and relations from their own sketches that were unintended when they drew, sketches can be a stimulus. In other words, the success of a design process hinges on the ability of differentiation, being able to perceive new features and relations in sketches and generate interpretations of them. We found empirical evidence for that. Expert designers were more capable of associating features and relations with functional issues (Suwa and Tversky, 1997). Further, perceiving unheeded features and relations, which is difficult to do for novices, was the major driving-force for the generation of ideas for an expert designer (Suwa, Gero and Purcell, 2000).

3. Do expert designers have high ability of differentiation?

According to those findings mentioned in the previous section only, however, it is insufficient to verify the hypothesis that expert designers have high ability of differentiation as a genera learning ability. Their advantage of reading off new features and relations from their own sketches might be solely due to the richness of schemata they possess, as the schema-base learning theory claims. My previous work done with Tversky (Suwa and Tversky, 2001; 2003) on ambiguous drawings provides supportive evidence for the hypothesis that expert designers have high ability of differentiation.

Before mentioning the findings, I will briefly review what the task of ambiguous drawings is and how it relates to the notion of differentiation. Reversing interpretations of ambiguous figures, such as the famous duck-rabbit figure, is difficult in imagery. Chambers and Reisberg (1992) argued that seeing another figure requires changing perceptual reference frames -- the duck and the rabbit face opposite directions--, and that changing reference frames is more difficult in imagery. Rock (1973) has demonstrated that assigning a reference frame is integral to interpreting a figure. In general a drawing consists of elements arranged in space relative to each other and to a reference frame and perspective (Tversky, 2001). Interpreting a drawing means grouping certain elements and not others as well as assigning a reference frame and perspective. People unwittingly fixate to the particular groupings of elements and/or reference frames and perspectives underlying previous interpretations. This accounts for the difficulty, in general, of reorganizing perception.

Howard-Jones (1998) demonstrated fixation in an experiment on which ours was based. Participants were asked to generate as many interpretations as possible of a single ambiguous drawing. The typical pattern was a drastic reduction in the rate of generating interpretations after the first minute, the *fixation effect*. Fixation is a problem that plagues designers, indeed, all problem solvers. In order to avoid fixation, observers would need to coordinate two processes, perceptual reorganization of the elements of a drawing and conceptual generation of new interpretations. If a person has a high ability of differentiately reading off new features and relations in a drawing, that discovery could be a strong driving-force for perceptual reorganization and conceptual generation. This means that a task of ambiguous drawings of the kind that Howard-Jones designed could be a measure of the ability of differentiation.

We found that expert designers produced more interpretations than design students, students who did not study design, or office-workers whose profession was unrelated to design (Suwa and Tversky, 2001). The 2001 study was a modest study, with 10 expert designers, 10 design students, 11 office-workers and 22 non-design students. As a result of adding participants since then, the number of participants so far recently amounted to 23 expert designers, 27 design students, 20 office-workers and 37 non-design students. According to the ANOVA test, the same finding as in 2001 has been obtained; there are significant differences among the four groups, $F(3, 103)=19.2$ ($p<0.01$). The post-hoc Turkey test indicated that expert designers produced more interpretations than the other three groups, and that design students produced more interpretations than non-design students.

This research shows that expert designers have higher ability of differentiation than design students and design novices. Considering that the task itself and the drawings used are unrelated to design and does not necessarily require design knowledge, it is assumed that expert designers' ability of differentiation is a general learning ability. The finding that design students have higher ability of differentiation than non-design students is suggestive of a hypothesis that engagement in design may help foster the general learning ability.

4. Future work

Studying designers is not just for better understanding designers and design processes. It is expected to gain significant insight into general issues of learning, especially one that will contribute to demystification of the tacitness of expertise and the process of acquiring it. Studies on expert-novice difference are, of course, important. More important is, however, a longitudinal study of the process of novices' acquiring the ability of differentiation. How do young designers acquire the ability of differentiation as a general learning ability? How does it affect the ways in which they read off from their own sketches? How does it eventually help them generate creative design products? What kind of educational programs help them foster the ability of differentiation? I have made a hypothesis that a practice of meta-cognitive verbalization, a long-term effort of self-awareness and verbalization of one's own perception and body movements, is effective for fostering the ability of differentiation (Suwa, 2004; 2005). Meta-cognitive verbalization has two significances. One is, obviously, that a person's self-verbalization can provide precious data on the dynamic process of how the body of a cognitive agent is being situated in the surrounding world, how she becomes aware of some variables unheeded earlier, and how that relates to the acquisition of expertise. This is a kind of data that would otherwise, e.g. by objective observation, be impossible to obtain. The other significance is, I assume, that an effort of meta-cognitive verbalization will change the way in which a person is situated in and acts onto the surrounding world, and thus help her reorganize perception to the surrounding world. As discussed earlier, the way in which one's own body is situated in its surrounding world has many implicit variables. This means that meta-cognitive verbalization is a difficult and far-from-perfect effort. There will always be a gap between what a person's body really experiences and feels in the surrounding world and what she is able to verbalize. I assume, however, the existence of a gap would be no problem. Verbalization is a tool for changing the way in which one is situated in the surrounding world and thereby opening keener eyes to many unheeded variables, and eventually for fostering the ability of differentiation. In recent years I have been accumulating several case studies in many domains such as sports (baseball, ice-hockey, bowling and snowboarding (Suwa, 2005)) and tasting. In each case study, the target of examination is the process in which a participant to the experiment who wants to become better at some skills in the target domain gradually acquires those skills through a long-term custom of meta-cognitive verbalization. Similar studies in the domain of design, too, are significant future work.

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THE CAPTURE OF DESIGN EUREKA

Application of visualized analytic methods on real-world-design protocol

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Abstract. The present paper studies a particular thinking phenomenon in design—the so-called 'design eureka' which includes a 'bottleneck-problem' and a 'idea-eureka'. Four real-world protocols all experienced 'design eureka' in their design process are deeply investigated by a series of analytic processes. Two goals -the description and the explanation of 'design eureka' are attained. By the tables and network-figures of the analytic method, the actual evolutions of design thinking are firstly visualized and show out the place of 'design eureka'. Secondly, through the advanced content analysis, the evolution of 'bottleneck problems' and the 'exterritoriality' of design eureka are revealed and explained. The results indicate a kind of particular faith in designer's intention, which plays a central role of design-art creativity and makes design to go beyond problem-solving scope but near a kind of art-working.

1. Introduction

One of the most fabulous things in design is at certain point a novel idea occurs incidentally, and by which better solutions suddenly become possible. This particular phenomenon of design solution-discovery could be called as "design eureka". Experienced designers may enjoy this kind of eureka from time to time, but never be able to catch it methodically. The esoteric wonder as such defies simple explanation, but might not be totally ineffable. It is the intent of this paper to provide a way of conceiving this phenomenon of design eureka that hopefully can be in better position to understand it more clearly.

In cognition psychology, "eureka" is described as a flash of insight usually after a period of intense preparation during which the thinker is totally immersed in the problem and approaches it from all possible angles, but illumination tends not to come then. And then suddenly the solution arrives, not at the writer's desk or the composer's piano, but elsewhere entirely (Gleitman 1995). Psychologists propose that this kind of creative thinking may involve perceptual restructurings, conceptual reorganizations, and incubation effects. Although there are some researches about these cognitive processes, few theories really prevail.

Some studies of creative design observe this phenomenon as "creative leap" (Archer 1965; Cross 1997, 2001). The idea of a "creative leap" has for some time been regarded as central to the creative design process (Archer 1965). By the protocol studies, the creativity in design is observed closely and deeply, but some methodical defects exit in these researches, in which the discussions of designers' thinking are always full of subjective interpretations, guesses and uncertainties. Even if some important observations and interesting suggestions have been made therefore, these accomplishments are difficult to examine in detail because of the lack of clear analytic procedures.

As what the cognition psychologists has revealed about the "critical insight", this phenomenon of thinking happens in design, too. Design eureka is a real experience independent of the quality of design work and could happen in various designs. To clarify the thinking mechanism underlying this mysterious "design eureka", the present paper excludes the judgment of design work. To dispel the mystique of "design eureka", the present paper aims to develop an effective measurements to capture it as precisely as possible, and by which, the advanced analysis could have a secure basis.

2. Issues and Viewpoints

2.1. EUREKA AND BOTTLENECK

As the stories what design practices tell, no matter creative or not, design get into bottlenecks occasionally. The bottlenecks of design don't occur at the beginning of design, but only after some vain efforts of solving particular design problems. It is this moment of bottlenecks that indicates the limits of knowledge and heuristic reasoning in designers thinking, and therefore designers look for any inspiration for the situation of bottleneck. Usually but suddenly, "design eureka" comes out in the following period and always from elsewhere not in the memories. This phenomenon reflects a kind of pair-like relationship between the bottleneck and eureka, and represents a critical type of thinking different from the logical or heuristics ones but important for acquaintance with designers' thinking beyond rationality. The present paper defines the pair of "bottleneck" and "eureka" as two core agencies of "design eureka" whose meaning to thinking should be studied in a context containing both two.

2.2. EUREKA AND NAVIGATION OF PROBLEM LANDSCAPE

"Design eureka" is so sly to describe precisely, not to mention to explain it. Therefore the preliminary issue of research is how to describe this "event". The way we describe it reflects how we view design thinking. Design thinking can be viewed as a process of navigation in a "problem landscape". The landscape is created and recreated in response to each move of design decision, and is constantly in the state of flux. Therefore, design navigation is never a programmable journey in a static problem landscape. The fact is that there are very few cases in which design problems can be formulated once and for all at the beginning. Problem changes as design develops, design navigation shall be seen as a trip to the landscape which itself is reciprocally shaped by that trip.

According to several preliminary observations, design eureka functions more likely as an effective act of changing the problem landscape to become more plausible for forming solutions, rather than as an effective solution per se. In this light, "changing-problems" instead of "solving-problems" holds the key to the design eureka. Problem reformulation requires insightful perceptions that can be molded by diversified resources, sometimes are dubious heuristics, hybrid ideas, or even irrelevant analogies. Design eureka plays at strategic level that gives instructions to the lower level of design operations, and is affected by the designers' intentions/philosophies from the level at above.

From above viewpoints, the dynamic changing of problem landscape and its navigation develops a time axis of thinking events. And design thinking functions could be divided into three levels: intention-level, strategic level, and operation-level from the top. There are three main questions this paper try to answer that how design eureka act among these functions, when it comes out, and where comes from.

3. Protocol Analyses

This paper has collected twenty real-world design protocols, which came from different designers with different design programs, but all have experienced their own design eureka. For deeply analysis, four of the twenties were chosen according to their diversities, which are preferred by this research in order to find out the common mechanism underlying the apparent varieties. The more diverse these protocols are, the more representative the mechanism is. Designers were asked to report their design processes in order of time and avoid any additional explanations and judgments. Researchers should distinguish and remove the additions and clarify any confusion or ambiguity by checking with designers. Before any analysis, designers' oral reports were translated into literal protocols.

These four protocols and designers are numbered as 01, 02, 03, and 04. Protocol-01 is the shortest one but with clear phenomenon of design eureka as the others are. Protocol-01 is chosen as an illustration in this paper. The following introduction is a summary of protocol-01. Protocol-01 is a shopping-mall design. At the beginning, the client demanded that the building should display an image of the Liberty to present the project's name "New York", even if the building will stand in Taipei. Designer-01 almost could not accept this demand. He preferred the building to be "simple". But he still tried some schemes by massing study and refused to design in post-modern style that is preferred by the client. At first, the client cannot accept his proposal without any of the Liberty's image. But designer-01 never gave up his own desire of the simple. He reinterpreted what the client asked for an image of the Liberty as a desire of "the remarkable". In one hand, he explained to the client how the schemes perform the image of "New York" replacing "the Liberty". In the other, he tried to communicate with the client to conceive different ways to be "remarkable". After several presentations and communications, the client finally accepted one of designer's massive-remarkable schemes. But at this time, designer-01 himself reversed his scheme and looked for another simpler one. Although having proposed several massive schemes, designer-01 still has no idea about how to make the building simple but remarkable with the image of "New York". One day when he was thumbing through a magazine, a glimpse of a particular building picture fired him a flash of light. He transformed partial composition of the elevation of that building into a new concept of design. He was satisfied well with the new one. In a later review, designer-01 certified again that the simplicity of the new design is really what he has wished for.

3.1. ENCODING

The most critical difference between real-world-design protocols and lab-experiment ones is that real-world design is in a complete open environment and nothing is controlled by the researchers, even the factors studied. It is the key issue of this research that how to encode the openness of real-world design protocols, including openness of information and of situations. The way this paper studies such design protocols is to encode them into a table called as "the context-table". The context-table has two main targets: one is to show the episodes of designer's thinking which are some design segments according to designers' reports, and the other is to show their changing paths. For the former, we identify "eight factors" from protocols to describe the thinking episodes. And for the latter, we create a "time-axis" of description to reveal the sequential changing.

Even if the four protocols come from totally different designs, still there are some common structures in their high-level cognitions. At first, all of them have not begun from nothing but at least a requisite. The requisites always existed before design. Some are the requirements of clients as protocol-01, protocol-02, and protocol-04. And some are designers' own intentions as protocol-03. All of the four designs started after these requisites occurred. This research classified these requisites as "the premise", which means a particular privilege governing design at some degree. Secondly, all of the four designers reported their design processes including strategies, operations, results and evaluations, and problems they really encountered. All these processes and information are classified as "the thinking", which develops into the body of a design. At last, a real-world design is so open that unexpected things may come in and influence design. The unexpectedness results from that it occurred outside the territory of designers thinking and then is named as "the exterritorials"—a compound word of "exterior" and "territorial". By this classification of interior and exterior of thinking, this research encodes the open resources of design. And this classification reveals a question about the territory of thinking- what is the territory of thinking? We suppose that after a period of thinking, the thought will cultivate a field that is a collection of what has been thought and its direct associations. This field is the territory of thinking. All in the territory can be expected by this thinking. But outside the territory, there are unlimited content that this thinking has not touched and not been associated, which is "the exterritorials". If any of the exterritorials comes into the territory and makes work, it must inspire a surprised-feeling of the thinker/designer. And what will cause the exterritorials to come into the territory? It may be the continuous cultivation of thinking itself. This work could extend its territory but not inspire any surprising. Here needs some different ways to associate and to cause surprising. It must be an unexpected association that connects to the exterritorials unexpectedly. And the unexpected association needs particular unexpected event to fire. In these four protocols, what makes the unexpected association is always a particular unexpected event. The facts in the protocols have support our hypothesis.

From above, the context-table consists of three divisions: the "premise-division", the "thinking-division", and the "exterritorials-division". Eight factors are extracted from the protocols and classified into the three divisions (see Figure 1). The "premise-division", containing design requirements (abbreviated as "**Rq**"), design constraints (**Cs**), and designer's intentions(**DI**), should exit before design and in fact start design. It is the "thinking-division", containing design problems (**P**), design orientations (**Or**), design operations(**Op**), and performance evaluation(**E**), that actually perform design. In the "exterritorials-division", because there is no enough data for detail classification, there is no detail code but the exterritorials(**Ex**).

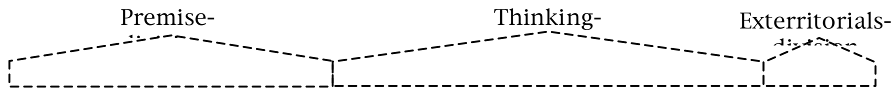
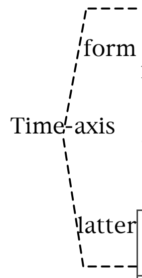
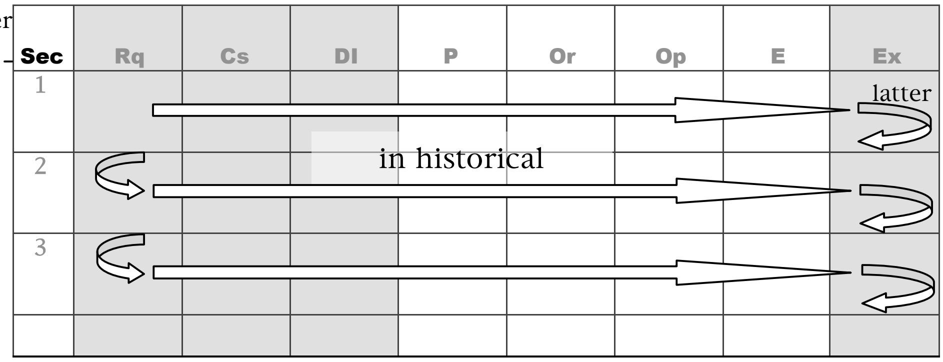


Figure 1. Conceptual frame of encoding system in the context-table





In the context-table, a protocol is divided into several design episodes named as “design section”. Every section unfolds a row of the context-table and consists of the eight factors in the three divisions. Each factors leads a column and each division stands on an area with their factor columns. So each protocol’s context-table contains several section-rows and eight factor-columns. There is a sequential rule governing the order of the three divisions and their eight factors (see Figure 1). According to their roles in whole design cognition, the sequence is determined and begins from “the premise-division” through “the thinking-division” to “the exterritorials”, from left to right.

All protocols were encoded into the context-table, statement for statement. First, according to the factor attribute of statement, each statement was noted as a suitable abbreviation on its matching blank. Secondly, according to content of a statement, we judged its relation with other statements and formulated its relation-equation. For example:

P1= DI1+Rq1.2 (1)

Equation (1) means that **P1** relates to **DI1** and **Rq1.2**. In fact, it may be that **P1** was a result influenced by **DI1** and **Rq1.2**. In later analysis, the relation-equations can be transformed into relation-networks in relation analysis. Here is the context-table of Protocol-01 (see Table 1). There are two kinds of empty blank: Blank-# and Blank-◎. Blank-# means that it has no other information from protocol but inherit the same information from above blank. For example, Blank-**Rq2** is noted as “#”, because of that designer reported nothing about that requirement, which means that no design requirement has changed and so the previous requirements had been maintained. On the contrary, Blank-◎ means that there was no information from designer's report and in fact nothing happened in the immediate thinking at all. All of he empty blanks of the "thinking-division" will be Blank-◎. Note "☆" represents the occurrence of eureka-idea and "※" the end of design.

TABLE 1. The context-table of Protocol-1 as the result of encoding

Sec	Rq	Cs	DI	P	Or	Op	E	Ex
1	Rq1.1 Rq1.2	Cs1	DI1	P1= DI1+Rq1.2	◎	◎	◎	◎
2	#	#	#	P2= DI1+Rq1.2	Or2	Op2	E2	◎
3	#	#	DI3	P3= DI3+Rq1.2	◎	◎	◎	◎
4	#	#	DI4	P4= DI4+Rq1.2	Or4.1 Or4.2	Op4	E4.1 E4.2	◎
5	#	#	#	P5= DI4+Rq1.2+ E4.2	◎	◎	◎	Ex5.1 =DI4+Rq1.2 Ex5.2 =Rq1.2 ☆
6	#	#	#		Or6	Op6.1 Op6.2 Op6.3	E6	◎
7	Rq7	#	#	◎	◎	Op7	◎	◎
8	#	Cs8	#	◎	◎	Op8 ※	◎	◎

3.2. ANALYSES OF PATTERN

3.2.1. Methods

In pattern analysis, we blackened those information-noted-blanks firstly. And then the thinking pattern showed up. This kind of pattern pictures the historical traces of thinking through design process. After removing content information, pure mechanism can be read from the patterns (Table 2). Two directional advanced analyses have been done (Table 3). Two directional advanced analyses have been done. One is horizontal an. One is horizontal analysis, whose goal is to observe detail thinking performance in each design section. The other is vertical analysis, whose goal is to observe the changing and developing of each factor. And the integration of these two analyses can induce the trends of whole design process.

TABLE 2. The pattern-table of Protocol-01

seq	pattern no \ factors	Rq	Rs	DI	P	Or	Op	E	Ex
1	4-001								
2	4-066								
3	2-014								
4	5-051								
5	2-025								☆
6	3-053								
7	2-005								
8	2-011						※		

3.2.2. Findings and Discussions

Followings are some major findings of pattern analysis:

1. The pattern can reappear the thinking history by the eight factors.
   (1) Various thinking phenomena, such as “bottleneck”, “eureka”, etc., have their particular patterns.
   (2) All trends of patterns develop toward right side—design operation and evaluation. This result conforms to the goal of design—to generate a physical form by operations.
   (3) Each of the four protocols has its own thinking pattern, which appears characteristics of protocol. The type of pattern seems indicating at some degree the style of design thinking.
2. Design eureka can be identified clearly from the thinking patterns.
   (1) Design eureka always comes from the exterritorials or their inspirations. Some idea-eureka happened just when particular exterritorial events were proceeding. And some happened when the exterritorial events have come into the thinking field and were combined with the originals.
   (2) There are two different preceding conditions of design eureka: one is with a problem-bottleneck, and the other is without any problem-bottleneck, even any problem sometimes.
   (3) After the occurrence of design eureka, the next pattern must start from the righter factor blank than the problem. It seems that eureka has stretched the trend of thinking toward design operation right side. This result represents the thinking function of design eureka—a “jump” to next more detail design stage.

TABLE 3. The analysis of the pattern-table of Protocols

<Protocol-01>

seq	pattern no \ factors	Rq	Rs	Dl	P	Or	Op	E	Ex
1	4-001								
2	4-066								
3	2-014								
4	5-051								
5	2-025								☆
6	3-053								
7	2-005								
8	2-011						※		

changing of problem

Eureka effects

design leap

the thinking trend of protocol

A problem becomes

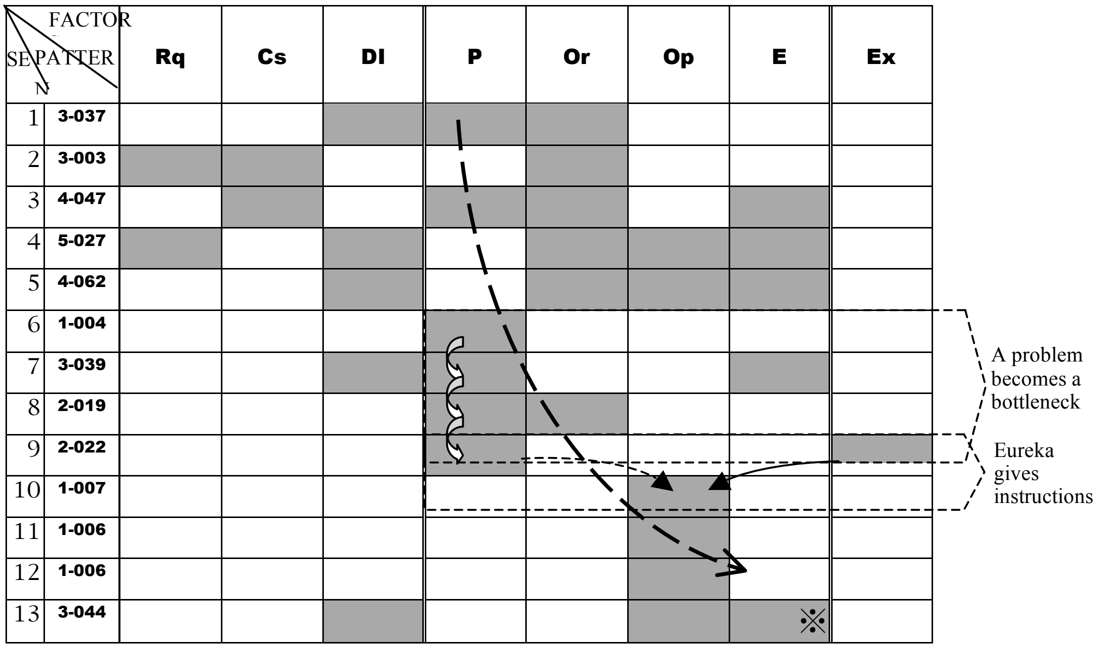
<Protocol-02>

seq	pattern no \ factors	Rq	Rs	Dl	P	Or	Op	E	Ex
1	5-004								
2	5-052								
3	3-040								
4	2-022								
5	2-026						☆		
6	2-023								
7	2-022								☆
8	1-007								
9	3-051								☆
10	2-026							※	

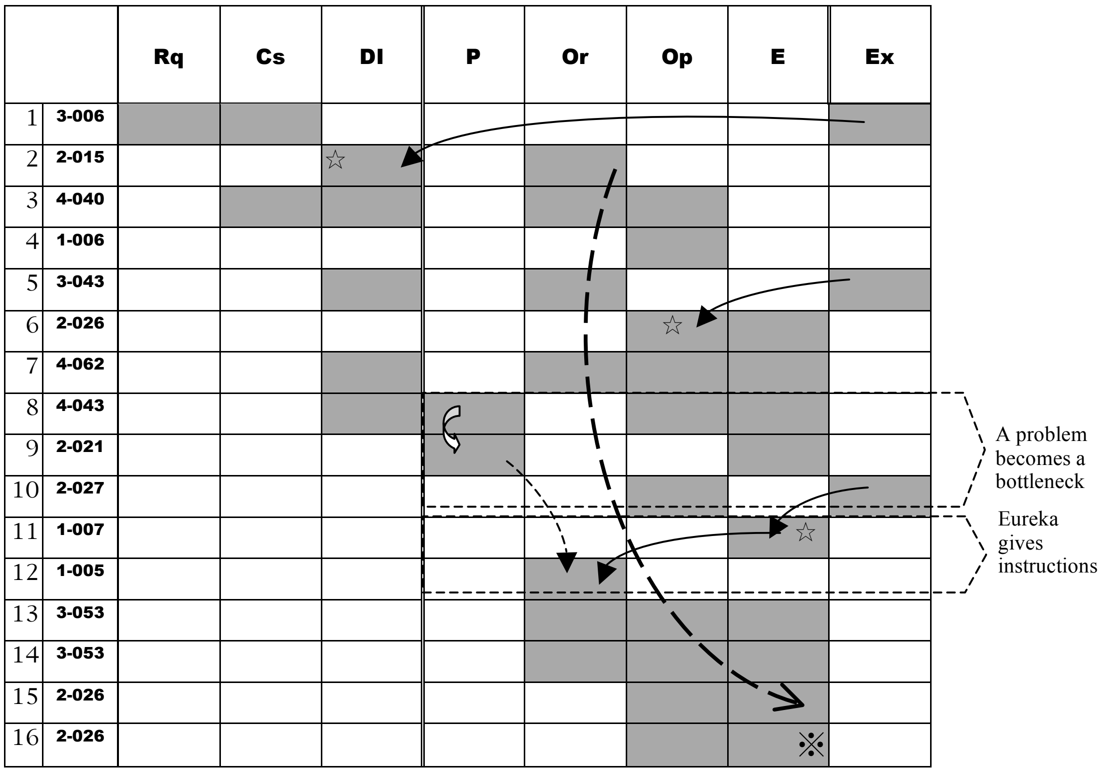
A problem becomes a bottleneck

Eureka gives instructions

<Protocol-03>



<Protocol-04>



3. Before the bottleneck-problem, there is always a collection of problems through one or more previous design sections. This finding indicates the evolution of design problem.
4. In the premise-division, the designer's-intention column changed mostly through sections. According to the patterns of four protocols, the designer-intention column changed always accompanied with a problem changing or a new operation. The results indicate a guidance of designer's intention to design.

3.3. ANALYSES OF RELATIONS

3.3.1. Methods

The analysis of factor relation is to study thinking process by the dynamic reactions between factors. The dynamic reactions can be described as a relation network. This kind of network aims no detail content, but to illustrate the information-processing flow behind the relations. From the network, this research figures out the role of design eureka in whole information-processing flow. Firstly, the previous formulations of relation in the context-table should be transformed into a relation-network (Figure 2), where the node of network is the matching blank in the context-table and marked with its abbreviation, and the arrow connects the node with other related nodes. Secondly, the thinking route should be identified from the network by connecting the arrows in the thinking-division. And the "shortest thinking-route" also could be identified by connecting the shortest arrows between sections. The third step is to analyze the network in order to infer the interactions between factors. The analyzed relation-network of protocol-01 is shown as Figure 3.

3.3.2. Findings and Discussions

Some results have been found as followings:

(1) The information of each factor could go into other factors and influence them. This phenomenon results in the flow of information between factors through design sections.

(2) According to thinking route, the major thinking developed along its route in the thinking-division and the other two divisions supplied necessary information to the route.

(3) Two special types of node can be identified: one is the gray node, which shoots most arrows to others and represents the most influence on others. The gray node is named as " the most influential node"; the other is the brown node, which receives most arrows from others and represents the factor which receives most attention. The brown node is named "the most critical-decision node".

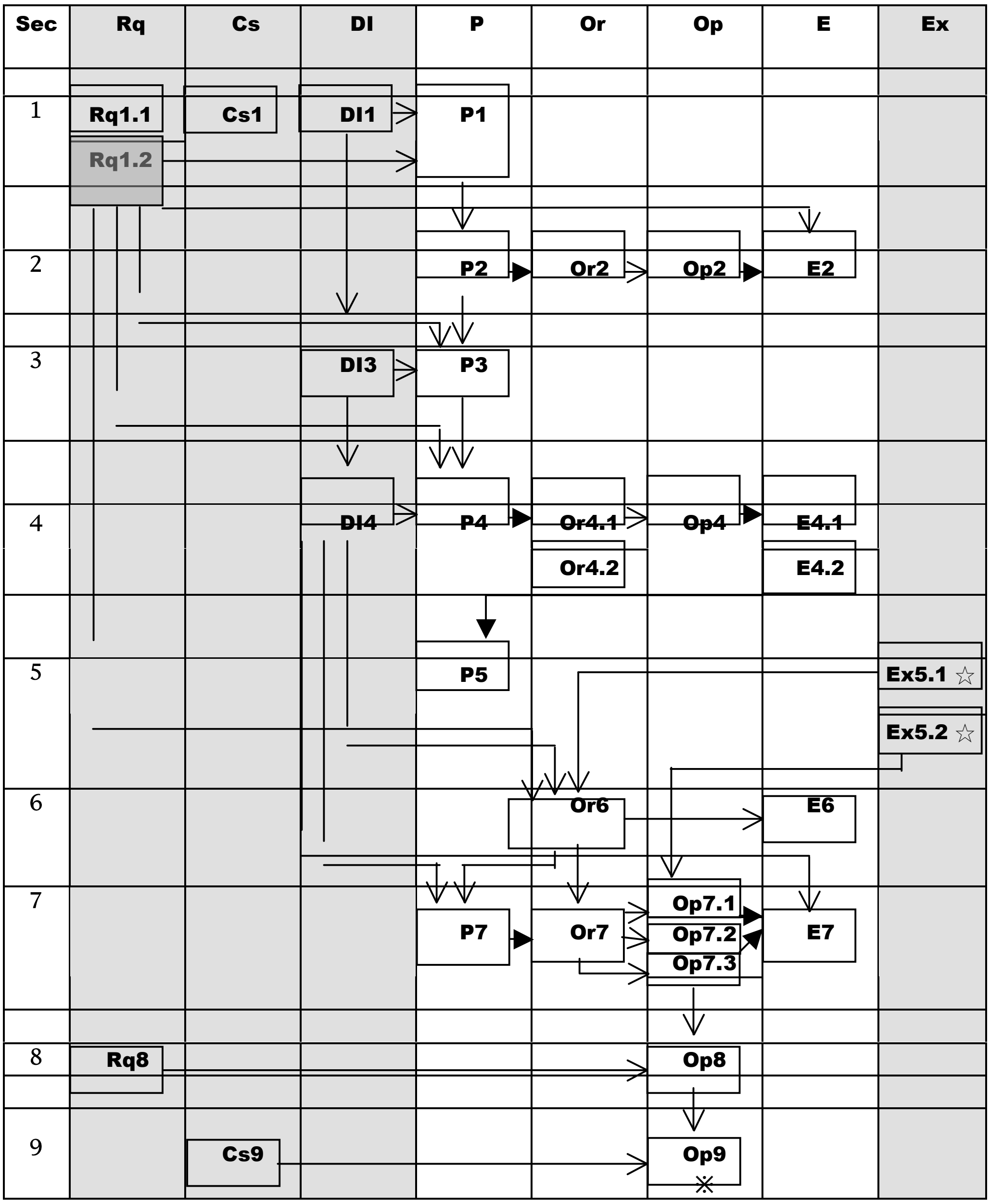


Figure 2. The relation-network of Protocol-01

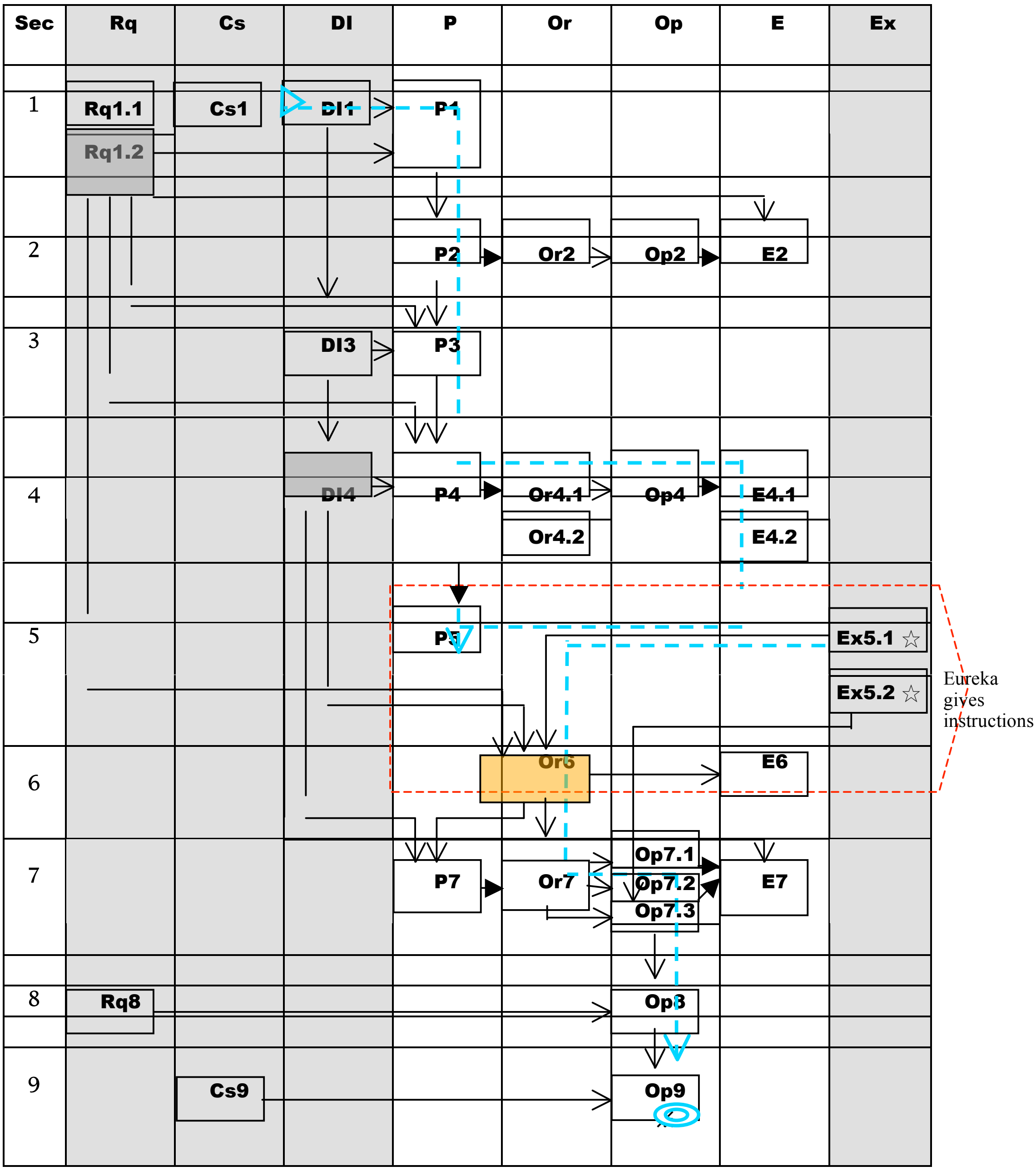


Figure 3. The analysis of relationship-network of Protocol-1

(4) There is one or more disconnected place of the thinking route, where is exactly the "design ditch". And it is exactly the design eureka that continue the stopped thinking route by "jumping" or "bridging" the "ditch".
(5) There are two ways that design eureka continues the stopped thinking: one is that design eureka starts a new beginning as a "jumping"; the other is that design eureka offers a connection with the previous stopping node and directs the succeeding thinking, as a "bridging".
(6) All of four relation-networks locate their " the most influential nodes" on particular "designer-intention nodes".
(7) Most of thinking-route started from design problem, but protocol-04's thinking-route didn't. Protocol-04 started from design operation and emerged the first design problem very late.

4. Discussions and Suggestions

By the visualized analyses, this research has pictured the scene of design eureka within the circumstance of real-world design as stated above. The real-world design is open enough to reveal the existence of the exterritory, the territory outside the field that the thinking has cultivated. Such a diverse territory is so important that offers a thinker the information he did not think before, but has never yet been included in the studies of thinking. The results of this research suggest that it is necessary to improve our instruments to catch real thinking characteristics, and the methods this research applied could be offered as an example.

The pattern of thinking changed as design developed, and can be regarded as the changing landscape of design navigation. What made the landscape change are the eight factors, and different protocol has its individual type of landscape, which reflects at certain point the style of its design thinking. It could be studied further.

Besides the results of analysis, there are some findings disturbing some typical viewpoints of human thinking. A finding about design problem comes from the absence of it at the beginning of design. In Protocol-04, design problem didn't appear until the middle stage of design when most of form has been generated and is very good. Such design event indicates that the designer didn't recognize any problem during that period, and if not problem-solving, what did the designer really have done and how might that thinking? This case offends the opinion that views design only as a kind of problem-solving and suggest that we should reconsider the meaning of "design problem" for real human thinking, but not only for artificial thinking.

According to this research, design problem is not necessary to be functional requirements as some other researches have conceived, all of these four protocols got their problems and bottlenecks little related with clients' brief but much with designers' own intentions. We argue that it is this way that designers devote themselves into design, and then makes design thinking to go beyond the problem-solving scope and into the art-working one.

Acknowledgements

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SESSION TWO

Ethical aspects of the product design process
P. Lloyd, W. van der Hoog & I. van de Poel

Dual protocol analysis based on design information and design process
Y.S. Kim, S.T. Jin & H.S. Lee

The nature of creativity in design
H. Casakin & S. Kreitler

A cognitive model of the engineering design mind
J.S. Elias & S. Dasgupta

JS Gero and N Bonnardel (eds), *Studying Designers'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 57-70

ETHICAL ASPECTS OF THE PRODUCT DESIGN PROCESS

A Protocol Study

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Abstract. On the face of it designing would seem to be an ethical activity as design often means prescribing how people should behave. Producing things that are better functioning, more beautiful, or that simply meet a client's needs are all aspects of designing that could be regarded as ethical. Yet, although the products of design have been the subject of ethical analysis (Winner 1980; Verbeek 2002), the process of design has received remarkably little attention. This paper looks at how ethical issues are dealt with during the design process. We have done this in a protocol study of fourteen industrial design engineers. We find, according to our hypotheses, that ethical issues in designing originate mainly from analytical discourse; that designers have a broadly utilitarian outlook, looking at the consequences of their design decisions to gauge their moral character; and that female designers display more of an 'ethics of care' than male designers, looking to make the products of the design process safe and inclusive.

1. Introduction

Ethics, like design, is concerned both with how things are, and how things should be. In this sense both disciplines have descriptive and prescriptive elements. In ethics the prescriptive elements outline theories of what constitutes the moral good—Utilitarian theories of ethics, for example, prescribe 'the greatest happiness for the greatest number'—while the descriptive elements look at peoples actual behaviour in ethical situations (Baron 1994). In design prescriptive elements outline what constitutes a good design process (Roozenburg & Eekels 1998; Cross 2000), while descriptive elements look at what designers do when they design (Lloyd and Scott 1994; Cross, Christiaans & Dorst 1995). In both fields behaviour coheres in the area between description and prescription. People often have an implicit model of what they do—derived from a combination of theory and experience—even if their subsequent behaviour deviates from this model. Indeed prescriptive models of what people think of as good design practice are often based on empirical observations of how designers design (Darke 1979).

What is interesting about designing from an ethical viewpoint is that, in producing something of putative value (be it functional, aesthetic, or ethical) a designer must go from the 'facts' of a situation, often laid out in a design brief, to the 'value' of a designed solution. In ethics this type of reasoning, inferring what *should* be from what *is*, is known as the naturalistic fallacy and there is a prima facie case for thinking designers guilty of this when they arrive at what they consider to be artefacts of value. On closer inspection, however, it is apparent that in design reasoning there is often an implied or suppressed theory of value behind the word 'should'. A functional, aesthetic, or ethical model of what is good is being assumed rather than made explicit. The question we are interested in answering in the present paper is what types of implicit ethical judgements are being made during the process of design?

In previous studies of designers (Lloyd & Busby 2003) we have looked at what we have termed micro-ethical situations; how ethical issues arise during the normal course of designing. This is in contrast to more conventional ethical analyses of design (Biosjoly 1987) that have focussed more on the 'big' ethical decisions of the design process as a whole ('should X have done Y?' for example). While a micro-ethical approach has proved productive, and provided a 'real' context for ethical-decision making in design, what it lacks is an explicitly ethical focus to the problem in hand. For this reason we decided to carry out a protocol study of a number of designers solving a design problem with obvious ethical implications.

There were several advantages of using a protocol analysis methodology for this study. First, by concentrating on verbal data we were able to focus on the reasoning processes of the designing participants. Second, we were able to fully control the task that we gave participants. Third, we could compare a relatively large amount of participant designers solving the same problem (large in these types of time-intensive analyses being more than five people).

We formulated a number of hypotheses to focus the study with the data being coded accordingly:

- *Ethical discourse will be analytical in nature, not synthetic.* If we divide the design process into analytic phases, where information is gathered, analysed, discussed, and evaluated; and synthetic phases, where solutions are generated, then we would expect to see more discourse about ethics in the analytical phases of design. This relates to our second hypothesis in that we would expect the consequences of solutions generated to be discussed in some sort of evaluative framework.

- *Designers will have a broadly utilitarian outlook.* We expected the ethical basis on which designers would judge their designing to based on the 'greatest happiness' Utilitarian principle mentioned earlier. This is because design is largely perceived as making things quantitatively better, and the users of design happier. Utilitarianism is a form of consequentialism, as it focuses on the consequences of actions. This contrasts with both non-consequentialism, which focuses on the ethical character of the action itself, regardless of the consequences, and virtue ethics, which focuses on the moral character of the agent carrying out the action.
- *Female designers will have more ethical discourse than male designers.* This hypothesis follows Gilligan's (1981) view that females display more of an 'ethics of care', considering the human issues of a situation rather than the technological issues, stereotypically a male area.

2. Method

The participants for the study were final year Industrial Design Engineering students studying at the TU Delft in the Netherlands. There were 14 participants (8 male, 6 female) forming 7 pairs (3 male-male, 2 male-female, 2 female-female). Participants were paid a nominal fee for their time. Pairs of designers were used because it was thought that this would make for a more natural verbalisation of reasoning and explanation, though obviously no claims can be made for verbalisation representing cognitive activity.

The task involved the design of a realistic toy-gun and was given in the form of a brief from a fictitious US toy manufacturer. There were three key elements. First, marketing had shown a demand for realistic-looking toy guns, particularly those seen on television in recent wars. Second, developments in technology meant that laser-sighting was now viable for the toy market, and that gaming could take place at the system level. Finally, there was a wish that the design consider girls as users, as well as boys, for the target age-group of 8-14 year olds.

Participants were sent the task two days before the design session so as to familiarise themselves and prepare for the exercise. The sessions themselves were held in a product usability laboratory and were recorded on video and audio tape. Designers were told they could bring along their usual designing materials. Sketches and presentation drawings made during the session were left behind. The design sessions lasted two and half hours on average.

2.1 TASK ANALYSIS

The design task contains a number of obvious, though implicit, ethical issues; indeed it was chosen for just this reason. First, playing with guns means encouraging aggressive behaviour; behaviour that we might not wish to encourage or reinforce. Second, imitation guns could be (and have been) used in real situations both for criminal purposes like aggravated theft, but also by deliberately scaring people (for example by training a laser sighting dot on somebody). Third, children could be confused with carrying a real gun if a play situation were taking place in a public space, which might endanger them. Finally, the inclusion of girls into the target consumer group indicated issues of equality, often taken to be ethical in nature.

These issues relate to different theories about ethics and we were interested in how designers would respond to this brief. One could for example argue that the good consequences that a game affords, for example the social contact, learning, or pleasure, outweigh the 'negative' consequences outlined above.

2.2 PROTOCOL ANALYSIS

Following the studies the videos were fully transcribed and analysed in a number of phases. The first phase looked at the difference between ethical utterances and non-ethical utterances during the design process. What constituted an ethical utterance was determined in a number of ways. First, we defined certain aspects of the design problem as ethically relevant prior to the protocol studies and utterances focussing on these issues where coded as ethical. Second, participants themselves came up with ethical problems that we had not thought about (for example the threatening nature of the laser sighting system). Third, we looked for utterances that could be construed as ethical in that they referred to ethical concepts like 'good', 'bad', 'fair', or 'unfair'. We were also alive to utterances using the word 'should' as this often refers to an implied (ethical) theory.

The second phase coded utterances at the different stages of the design process. The coding followed the analysis > ideas > concepts > details > evaluation model of design that is used in the design education at the TU Delft and has been used as a coding framework in previous papers (Lloyd 2002). We were interested here both in the stage at which ethical discussion took place, and also whether the detail of the design had any effect on the ethical discussion coded in the first phase.

The third phase of analysis coded utterances into 'analytic' or 'synthetic' types. The thinking here was to look in a more detailed way at patterns of actual design reasoning, which often follow a more circular path than a stage model of design might suggest (Cross & Dorst 2003, March 1976). Here we were attempting to see whether ethical issues formed part of the solution generation process, possibly being combined with aesthetic issues, or whether ethical issues were more analytical in nature, as we expected. Examples of analytic utterances are something like “so these components fit together in a modular way…” and “but that’s going to fire in all directions”. Analytic utterances tend to be interpretive comments, filtering the data of the design situation. In contrast synthetic utterances involve taking the solution a step further. Examples here are: “ok I think we should have rubber for grip…”, “how about a send and receive signal for two way communication?”. Obviously the distinction is fairly rough and dependant on how one interprets utterance as the basic analytical unit. What we were trying to do was to keep the coding scheme fairly simple and force all utterances into one or other category.

Along with this quantitative coding of the data was a more qualitative analysis looking at specific instances of the content, often leading from the coding scheme, of what was being discussed or argued. This took a more discourse analytic approach, looking for the ideologies behind the words and relating what was said to ethical theory.

3. Results

Generally speaking each protocol could be divided into three overall stages: problem analysis, solution development, and presentation. This roughly follows the educational model of industrial design engineering taught at the TU Delft (Roozenburg & Eekels, 1998). Final presentation drawings were produced by all pairs of designers, an example is given in figure 1 below.

In most of the protocols the formulation of the design goal formed the end of the problem analysis phase, and the beginning of the phase of formal solution development. The design goal tended to guide further solution development, constraining the space for possible alternative solutions. In most of the protocols the ethical issues raised were either ignored or partially resolved in the formulation of this design goal. For example in protocol 3 a design goal was formulated around the idea of encouraging teamplay: ‘so that the individual user doesn’t have to walk the streets with a realistic toy gun’. The ethical problem concerning individual users was deliberately ruled out:

> “A gun-game system that encourages team play, and discourages individual users” [Protocol 3, 0:31:44]

In Protocol 3 the ethical issues resolved in the formulation of the design goal were not returned to during subsequent solution development. This contrasts with protocol 1, where the number of ethical issues discovered during problem analysis and the reflection upon those issues during solution development were almost equal. Figure 1 shows typical final presentation drawings.

Figure 1a. Final presentation drawings for protocol 1 showing what the designers termed 'archetypal forms'

3.1 DESIGN ACTIVITY

So far three of the seven protocols have been analysed in detail and coded according to the categories outlined in section 2.2. The third category looked at analytic and synthetic utterances, while the first category looked at whether an issue could be classified as ethical or not. Table 1 below shows the results of this coding.

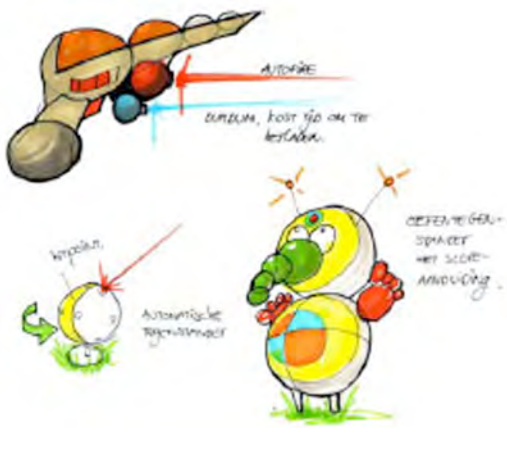

Figure 1b Final presentation drawings for protocol 3 showing a more 'friendly' form for the gun.

TABLE 1. Type of design activity by protocol number.
Note: protocols 2, 5, 6, and 7 have not yet been fully coded

	Protocol number						
	1 (MM)	2 (MF)	3 (MF)	4 (FF)	5 (MM)	6 (MM)	7 (FF)
Analytic design activity	37%		59%	45%			
Ethical issues	7		14	15			
Synthetic design activity	63%		41%	55%			
Ethical issues	2		5	1			

In protocols 1 and 4 ethical issues appeared mainly in analytic utterances (note: these are not necessarily in the analysis phase of design) suggesting that the ethical issues were being derived from the design situation not driving solution development. Overall the identification of *new* ethical issues did not occur in synthetic utterances. However the point where ethical issues did emerge in synthetic utterances was characterised by reviewing a proposed solution against existing ethical criteria. For example, the participants of protocol 4 reviewed their the development of their ideas to their particular design goal, which entailed that children should make use their imagination:

> "But with this lever you can easily imagine that it is a real gun, just like loading your gun" [Protocol 4, 1.39.32]

These results seem to confirm hypothesis 1 although the picture is far from clear given that the distinction between analytical and synthetic utterances was sometimes difficult to judge. The distinction often seemed to turn as much on the emphasis of particular words – turning an analytical remark into a suggestive remark for example – as on the words themselves.

3.2 ETHICAL ISSUES DURING DESIGN

Table 2 gives an overview of which ethical issues were discussed in individual protocols. The issue of 'young children in dangerous situations' was recognized by all pairs of designers, and the issue of designing guns for girls by almost all pairs. What is perhaps more surprising is that only three out of the seven groups considered the aggressive behaviour that playing with guns might encourage. All three of these pairs (protocols 2, 4, and 7) disapproved of playing with toy guns in general.

TABLE 2. Identification of ethical issues by protocol number.
(see Task Analysis, section 2.2)

	Protocol number						
Ethical Issue	1 (MM)	2 (MF)	3 (MF)	4 (FF)	5 (MM)	6 (MM)	7 (FF)
Aggressive behaviour		X		X			X
Threatening realism	X		X	X	X	X	
Threatening laser sight	X		X				
Dangerous situations	X	X	X	X	X	X	X
Involvement of girls		X	X	X	X	X	X

We were also interested in the type of justification given in discussing the ethical issues involved in the problem. These were divided according to the standard theories of ethics described in section 1 (hypothesis 2). Table 3 shows that hypothesis 2 was confirmed; most designing pairs did justify their decisions on the basis of either good or bad consequences (i.e. the solution causing net pleasure or pain). An example of this can be found in the following excerpt from protocol 1, in which the designers consider the misuse of toy guns:

> "[we need the gun] to be part of a bigger thing, so that you can never use the gun separately, because people use these kind of things for criminal stuff. They are really similar to real guns" [Protocol 1, 0:10:52]

Other forms of ethical justification were noted however. In protocol 5, for example, the participants discussed the idea that it was the responsibility of the client to remain within the law:

> "But the client wants something like… they want to stay within the realm of the law and still sell as many as possible, whether they are realistic or not. I don't think the client would mind as long as he sells plenty." [Protocol 5, 0:11:40]

In protocol 3, the participants stated it would be more challenging for them to design a non-realistic toy gun, integrated in a realistic form of play. The participants justified this approach by referring to their creative value and design skills, an approach we labeled as 'professional pride':

> "As a designer, I would prefer the freedom and the challenge of designing this one..."(protocol 3: 2.10.52)

TABLE 3. Types of justification according to protocol number.

	Protocol number						
Type of Argument	1 (MM)	2 (MF)	3 (MF)	4 (FF)	5 (MM)	6 (MM)	7 (FF)
Utilitarian	X		X	X	X	X	X
Duty	X						X
Virtue		X					
Law abiding					X		
Professional Pride			X	X		X	X

3.3 MALE AND FEMALE DIFFERENCES IN DESIGNING

Overall the female participants in the protocols expressed more concern for the safety and well-being of the child users of the toy. For example, following the unarticulated premise that it is important for children to be stimulated to use their imagination, the two female participants of protocol 4 referred to the lack of fantasy when playing with realistic toy guns:

Person A: I think that during play you should use your imagination…

Person B: why does it have to be realistic in that case?

Person A: Yes, exactly. Because if it is realistic, then you won't be able to use your imagination

[Protocol 4, 0:06:55]

Another example from protocol 4 focuses on the competitive element to games involving toy guns:

Person A It's a silly game isn't it, playing that you are shooting people dead? That's strange isn't it?

Person B It's about who wins.

[Protocol 4, 0:37:14]

The female participants also tended to take a wider view of the game situation, thinking about the other parties involved when children play with toy guns, particularly parents. The male participants tended to adopt a single point of view keeping within the narrow frame of game play. In protocol 2 the male designer describes the difference between a paintball gun and a toy gun:

"the advantage of a paintball gun is that when you are hit you're out of the game. You get, erm, ruled out, which gives you more of an idea that you are dead. Maybe that's less fun, but it could lead to reflection." [Protocol 2, 0:06:12]

The male-female combination of protocol 2 rejected the terms of the existing brief, designing for an older age group (16-19 year olds) and developing an idea they termed ‘team love sniper’ (figure 2)

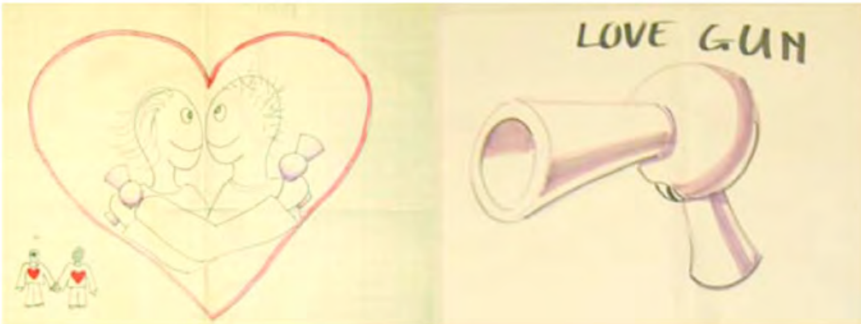

Figure 2. The ‘team love concept’ redefining the concept of a gun game system

Hypothesis 3 stated that female designers would demonstrate more of an ethics of care, and this was generally the case in the protocols. The females adopted a more questioning attitude to the brief, and a more inclusive view of the parties involved in the assignment.

3.4 AESTHETICS AND ETHICS DURING DESIGNING

What was of note in one of the protocols (perhaps as one might expect more generally in design) was a close relationship between aesthetics and ethics. An example of this came in Protocol 1 where an aesthetic concept—‘coolness’—was discussed in relation to an ethical concept—‘making the gun non-threatening’. The designers summed up the problem:

> “How do we design a cool gun that’s not threatening… one that you’d actually like as an 8 to 14 year old boy?” [Protocol 1, 0:11:53]

When the designers suggest that perhaps an exaggeration in proportions could make a toy gun look cool, the non-threatening nature emerged with the remark that it shouldn’t look “too soft or organic”. Figure 3 shows the pattern of reasoning involved in this episode.

Another example of the interaction between aesthetic and ethical concepts was the relationship between the form of the gun and the feeling of power that it gave to the user. The participants of protocol 1 discuss a form that transmits a feeling of power:

> “it should remain a gun… it’s about the idea that you aim at someone and experience having the power to shoot somebody.” [Protocol 1, 0:24:35]

This ‘feeling of power’ however, is not seen by all as something worth designing:

> “I think it will give the person [pointing the gun] a lot of power. That’s not so good.” [Protocol 4, 0:48:50]

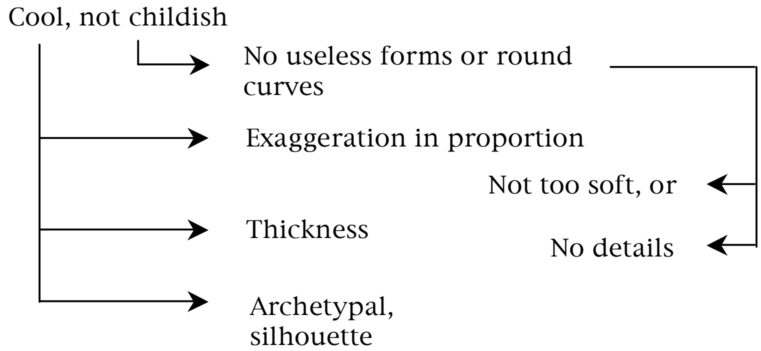

Figure 3. Development of the ‘cool but not threatening’ aesthetic concepts in Protocol 1 (see also figure 1). The left column shows attributes of the ‘cool’ concept, while the right column shows attributes of the ‘not childish’ concept.During the discourse the concepts are interspersed.

There are two issues here. The first is that the aesthetics of the gun (including the form, material, weight, and sound) can conspire to give a feeling of power to the user. The second is the ethical idea about whether this feeling of power is a good thing for children to have, or to develop. The aesthetic changes the designers discuss can thus have a close relationship with subsequent ethical concerns.

4. Discussion

The set up of the study allowed one ethical decision that none of the designers took. That was to refuse to take part. In giving a nominal fee to the participants we tried to simulate a real situation in which a designer receives a fee for their design proposal. Refusing this fee would indicate a desire not to explore the issues involved in the problem. Although several of the (mainly female) participants disapproved of designing guns, all completed the task. This might indicate that designers would rather try and creatively engage with ethically problematic issues than ignore them altogether or leave them to someone else. One of the more implicit ethical issues in the brief was the idea that designers might think that solving the problem would make them a worse person in some respect. It would seem that designers see the knowledge that designing brings as a positive thing, even for ethically questionable briefs.

The ethical status of design knowledge is not a simple issue, and is brought to the fore in situations where imagination is required in solution development. In one of the protocols the designers mention the idea of giving children who have been 'shot' in the game situation an electric shock. The idea is brief, and not developed at all, but the fact remains that for designers ethical boundaries have to be fluid in order to fully explore the imaginative possibilities of a brief.

Hypothesis 3 proved to be correct. The female designers were much more reticent about designing a gun or gun-system than the male designers, focussing instead on how to make such a system safe and inclusive. Several of the male-male pairs of designers got quite excited about their solution development, appearing to leave behind any initial ethical concerns. Seeking a creative solution with the given technology became much more of a goal for them.

Where ethical reasoning did take place it was mainly consequential in nature (confirming the second hypothesis) but other ethical strategies were in evidence. Interesting was an interaction between the design solution and the law. Several designers questioned whether a realistic gun would be allowed under current legislation but judged this issue outside the realm of their responsibility. This points up a common perception among industrial designers (in common with biotechnologists and in contrast to architects (Lagueux 2004)) that they are not ultimately responsible for the ethical aspects of their work. This defers responsibility for the product to the client, which is surprising in this experiment given the vague client details of the set-up.

The first hypothesis, that ethical issues would occur in analytical design activity, was largely confirmed and reveals something about the strategy of designers when dealing with ethical concepts. What one might conclude from the protocols is that there are two distinct ways of dealing with ethical problems. One strategy tries to resolve the ethical issues in the problem formulation. If that is successful (in the view of the designers), ethical reflection is not likely to reoccur in the synthetic phase of designing and in aesthetic judgements made about the solution. The other strategy formulates the ethical problem more explicitly as a conflict or trade-off that is further elaborated during the synthetic phases and by making aesthetic judgements designers get a clearer view about the ethical implications of the solution.

The protocol analysis methodology used in the study proved suitable in accessing the ways in which designers think and talk about ethics during a design process. Although obviously no claims can be made for capturing cognitive activity, since participants designed in pairs, the steady stream of conversation during the process provided a good indication of what the participants were concentrating on, and how they were resolving the issues presented in the design brief. Coding the protocols, as always, proved difficult, especially consistently sorting the data into synthetic and analytic utterances. This may in part be due to non-verbal activity (Lloyd, Lawson and Scott 1995) and future studies will take account of this.

5. Conclusions

In asking 7 groups of 2 industrial design engineers to complete the toy gun design task we were hoping to gain insight into how designers deal with ethical problems in the design process. Following a protocol analysis methodology we showed the range of arguments designers use in dealing with ethical issues. Not surprisingly we found that, in the main—though certainly not exclusively—designers focus on the consequences of their actions when making design decisions touching on ethical concerns. We noted differences in approach between male and female designers, the latter showing concern about the effects of the design on a wide range of stakeholders, the former perhaps more imaginative in their solution proposals. We also noted the close relationship, but ultimate exclusivity, between aesthetic and ethical judgement. In conclusion it seems that industrial design engineers are able to identify and adequately discuss the ethical aspects of their design activity, but not in highly sophisticated ways, and often in a surprisingly cursory manner. Further studies are looking at a typology to classify ethical ideology for designers.

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DUAL PROTOCOL ANALYSIS BASED ON DESIGN INFORMATION AND DESIGN PROCESS: A CASE STUDY

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Abstract. A case study has been conducted to explore design activities of four expert designers through protocol analysis. We examined relations among design information, process patterns and solution qualities with two complementary coding schemes based on design contents and design process. Relation between personal creativity modes and design activities has been examined as well. Regarding design process, an adequate distribution of activities in process may be necessary to bring out a good solution. It seemed that the more design contents about context, external knowledge, and general feature are used, the more unique design concepts are made. Regarding personal creativity modes, not much of differences in design activities were observed while only a few relations between designer's personality and design activity were observed. The fact that the designers participated are all experienced designers could explain this.

1. Introduction

Among the empirical research methods for analysing design activity, protocol analysis is the one that has received the most use and attention in recent years (Cross et al. 1996). It has become regarded as the most likely method to bring out somewhat mysterious cognitive activities of designers. The objective of this study is to explore design activities such as design cognitive process and design information through protocol analysis of design sessions of expert designers. We examined relations between design information which designer mentions in problem-solving, design process patterns represented by protocol data, and design solution qualities. Especially we instituted dual coding schemes based on design information and design process.

With the purpose of identifying relations between various cognitive characteristics and design creativity, an experiment was conducted earlier using personal creativity mode test, constructive perception test, visual reasoning test, spatial perception test and idea generation test, and design task test for students with varying level of experiences in design (Kim et al. 2005). In this study we try to find relations between cognitive personality by personal creativity modes and design activities represented by protocol analysis.

2. Experimental Design

Tests conducted in this experiment and experimental methods are described below.

2.1. PERSONAL CREATIVITY MODE TEST

Based on Jungian creativity theory, Professor Wilde of Stanford University developed a *personal creativity mode test* (PCMT) (Wilde 1999). PCMT has been used at many universities including Stanford and Sungkyunkwan in composing design teams in project-based design courses (Kim and Kang 2003). The personal creative modes are intrinsically related with the personal cognitive preference (Wilde and Labno 2001). Based on the cognitive theory of Jung, personal cognitive preferences can be identified based on four aspects, perceiving/judging preference, factual/conceptual perception, thinking/feeling judgment, and introverted/extroverted cognitive motivation. With these cognitive preferences, eight different modes of creativity can be identified as shown in Table 1. Also recently, the traits of the creativity modes have been described by another research (Levesque 2001). Each participant in this test did computer-based PCMT before design task test.

TABLE 1. The Eight Personal Creativity Modes

	PERCEPTUAL MODES		RESPONSIVE MODES	
	Conceptual (Intuitive)	Factual (Sensing)	Objective (Thinking)	Subjective (Feeling)
EXTRAVERTED MODES	Synthesizing	Experiential	Organizing	Teamwork
INTROVERTED MODES	Transforming	Knowledge -based	Analysing	Evaluating

2.2. DESIGN TASK TEST

The specific task given for the design task test (DTT) is explained in the form as given in the test.

Design Assignment:
A Small Playground utilizing water in a Kindergarten

Seeing an existing playground in the kindergartens, there is no play tool that utilizes water. You should design a small playground utilizing water for kindergarteners. When designing the tool, you have to consider that children can easily touch and manage water and characteristics of water are used in its mechanism. It can be handled by one child but it is preferred that a group of children use it to play together. Play tool should be safe and it should be possible to play without swimming suit. Also, installation must be easy and it can be placed either indoor or outdoor with proper size.

2.3. EXPERIMENT

In the experiment, four expert designers over five years of design practice careers participated. The equipments used in this experiment for protocol analysis were as follows: Video camera & Pinnacle board, video presenters, and voice recorder, and video capturing program (Pinnacle Studio & TV Plus). The experiment setting is shown in Figure . Before giving DTT to subjects, we gave them small task as an exercise to practice 'think aloud' for 5 minutes. DTT was carried out for 60 minutes independently in a closed experimental environment.

3. Protocol Analysis Coding Scheme

Collected data were video data, voice data, sketches acquired from design task. We recorded all of voice data for protocol analysis. Video data was employed as support data and sketch was used in assessing design solution.

3.1. INFORAMTION CATEGORIES

Information categories are divided as shown in Table 2. Each category addresses design contents with meaning and concept.

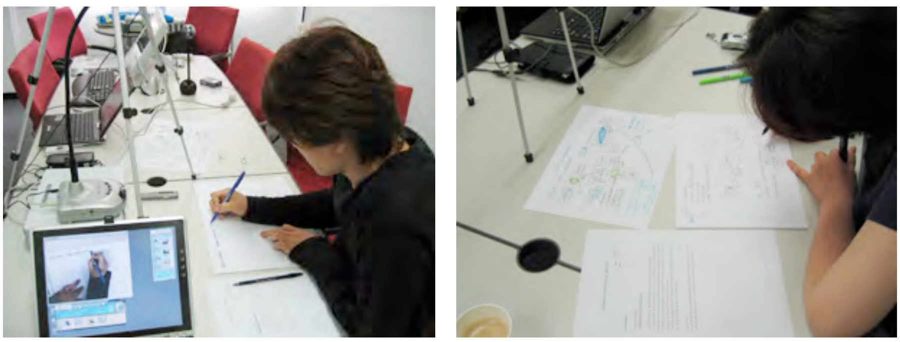


Figure1. Scene of Design Task Test

TABLE 2. Information Categories

Main categories	Subclass	Examples
Form visual factor	**Overall Shape (OS)** -Main object, Size, Color	with many curved shape
	Component Shape (CS) -Unit	speaker, LCD, fountain, lighting
Function	**General Feature (GF)** -Common function, Usage	able to hold water, drain naturally, gives sense of stability
	Technical Feature (TF) -Explicit function, Operation	Bore a hole, attach a foothold
Context	**External Knowledge (EK)** -User social context	Kindergarten, seven-years-old, pad dle their feet in water
Human	**Physical Elements (PE)** -Body elements, Human moving, Gestures	dip their feet, sit
	Mental Elements (ME) -Feeling, Responses	Boring, bears no burden
Designer	**Intent (IN)** -Domain knowledge -Designer's prediction or Judgment -Process management	What children want, it appears to b e a big fountain, lighting is needed too First of all, basic analysis about target user is needed.

In Table 2, categories are largely classified into form, function, designer, human and context so as to correspond possible overall data. Form is visible factors, which is divided into overall shape (OS) and component shape (CS). Function is referred to general feature (GF) and technical feature (TF). GF is a functional definition forming product characteristics and TF is a content to look for technical solutions. Human category contains physical elements (PE) and mental elements (ME) such as user's movement, behaviour, psychological state, feeling and responses. Context is external knowledge (EK) regarding social relationship, context, and resource information associated with design problem. Especially, intent (IN) in designer category is related to designer's prediction and judgment, domain knowledge, process management. This IN content is an integral part of design process as it is clearly distinctive from other categories.

3.2. DESIGN PROCESS

The design process modeling basically consists of problem understanding phase, idea generating phase, and design elaborating phase. Goldschmidt (1996) used remarks (agenda, joke, miscellaneous) as a design activity in a coding scheme. In this study we used 7 activities for design process and added 'designers' informal remarks (A1) in order to capture the process for designer's informal issues. Especially, we divided the design evaluation activity into two steps (D4 & D6) in the whole design process. The first evaluation step is called D4 which can be considered as pre-evaluating step where judgment of ideas, problems, and design constraints are constantly happening before detailed design. However the other step, called D6, occurs during the course of elaboration design to re-evaluate problems found in the process so a design activity for an improvement can be triggered.

D1. Understand problem and user
: understanding design task, problem situation, user, and context
D2. Define constraints and requirements
: constraints, design objective, user and product requirements
D3. Generate idea: generating ideas, partial solutions, analogy
D4. Judge ideas and context
: previous design task judgment, idea evaluation
D5. Elaborate function and form
: finding technical solution, realizing function, and embodying shape
D6. Evaluate solutions: solution assessment, design problem-grasping
D7. Refine the solution: improving the solution
A1. Designer's informal remarks

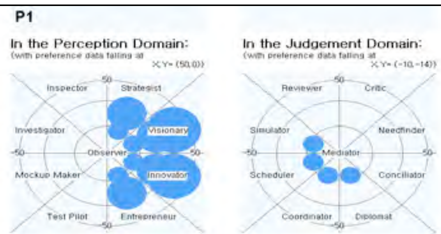
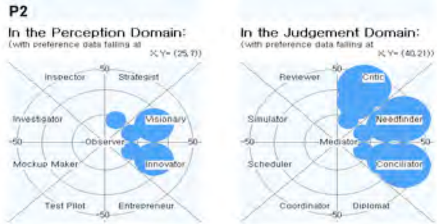
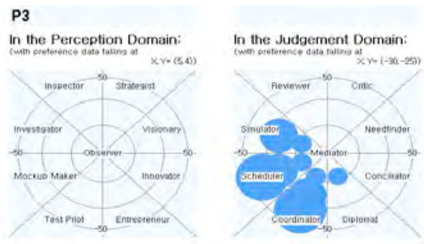
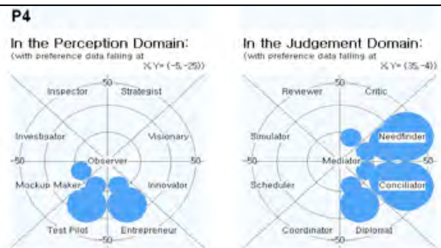
4. Results

The results of PCMT and DTT are presented as below and the results of examining the relations among design information, design process, the quality of solution and PCMT through protocol analysis are provided.

4.1. PCMT

Four designers' personal creativity modes and each mode's traits are provided in Table 3. As shown in Table 3, as dominant creativity mode, participant P1 has synthesizing creativity; P2, evaluating Creativity; P3, organizing creativity; P4, teamwork creativity.

TABLE 3. PCMT Results

Partici-pants	PCMT	PCMT Result Diagram
P1	**Synthesizing Creativity** : the extroverted conceptual mode : involves rearranging various elements into new configurations. : typical role - innovator	
P2	**Evaluating Creativity** : the introverted feeling mode : entails comparing perceived information and potential actions : typical role - needfinder	
P3	**Organizing Creativity** : the extraverted thinking mode : entails impersonal logical arrangement of external things : typical role - scheduler	
P4	**Teamwork Creativity** : the extraverted feeling mode : concerns control of or by external human emotional factors : typical role - conciliator	

4.2. EVALUATION OF DESIGN SOLUTION

A designer's aim is normally to achieve a high-quality design, with novelty or creativity being treated as only one aspect of an overall, integrated design concept (Kruger and Cross 2001). In this study, each solution was rated by 5 criteria of concept, aesthetics, functional utility, technical aspects, and usability. The scores are presented in Table 4.

TABLE 4. Scores of Solution Assessment in each Aspect (10 scale)

Participants	Concept	Aesthetics	Functional Utility	Technical Aspects	Usability	Sum (100%)
P1	8.5.	9.5	9.0	8.5	9.0	44.5(89)
P2	6.5	7.0	6.0	9.5	6.5	35.5(71)
P3	8.0	7.0	8.0	8.5	8.0	39.5(79)
P4	9.5	9.0	8.0	7.5	7.5	41.5(83)

4.3. DESIGN INFORMATION RESULT

We examined the relations among information categories, PCMT and design solution qualities. As shown in Figure 2, the amount of data flow in each information category shows consistency with a few exceptions. This result may demonstrate that design activities in expert domain are standardized to some degree and have a uniform pattern.

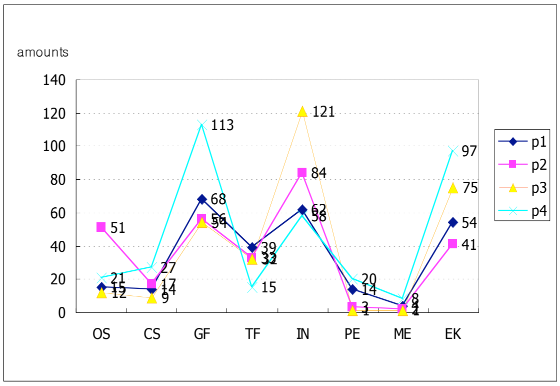


Figure 2. The Amount of Information Subclasses

TABLE 5. The Amount of Information Subclasses each Participant

Participants	OS	CS	GF	TF	IN	PE	ME	EK	Sum
P1	15	14	68	39	62	14	4	54	270
P2	51	17	56	33	84	3	2	41	287
P3	12	9	54	32	121	1	1	75	305
P4	21	27	113	15	58	20	8	97	359
Aver.	24.8	16.8	72.8	29.8	81.3	9.5	3.8	66.8	305.3

4.3.1. OVERVIEW OF DESIGNER'S DESIGN INFORMATION

P1's amount of information shows general pattern in overall sense and was least in amount. IN was less than the average but TF and PE were higher than the average. In case of P2, the amount of OS was relatively higher and amount of PE and EK were less than others. In case of P3, the amount of information was different from overall average. OS, PE, and ME were much less than the average, while IN was the highest among participants. The amount of information P4 mentioned was the highest, especially GF, PE, ME, and EK were the highest as compared to other designers.

4.3.2. INFORMATION AND PCMT

The information types used in design task varied according to PCMT types as you can see in Figure 2 and Table 3. For example, the information categories used by P4 in problem solving process showed more frequent use of vocabularies of 'human-related factor (PE, ME)' and 'context and external knowledge (EK)' compared to others having different types. In other words, he put relatively greater emphasis on user's physical status, context, social relationship and psychological state as compared to other designers. This coincides with the type of traits Levesque (2001) mentioned.

In case of P3, the frequency of vocabulary use related to designer's intention (IN) was greatly high whereas human-related factors (PE, ME) were hardly mentioned. These results can be interpreted as coincidental with the traits of scheduler having analytic and logical thinking disposition rather than emotional aspect.

4.3.3. INFORMATION AND SOLUTION QUALITY SCORE

a) As you can see in Table 4 and Table 5 the higher the scores on the concept, the more amount of External Knowledge and Context (EK) was observed. This relation shows that analogy from external knowledge and effort to comprehend design problem in association with social relationship or context bring out solid and original concept in designing. Designer's continuous endeavor to transfer his external knowledge into appropriate designing property could be considered as the main reason in establishing an original concept. Employment of external knowledge is shown in many occasions and this fact works as a design motive in establishment of concepts. In fact, P4's EK category includes playing with tubes, ropes, horizontal bars, seesawing and running, and such information occurred in P4 to help establish concepts. Note that a designer who comes up with a well-understood analogous concept may be able to manage a variety of concerns and insights by integrating them into an already coherent conceptual structure (Craig 2001).

b) Our assumption of OS in relation to the aesthetics could not be seen in this study. P2 has much OS but his score on aesthetics was not notable. The reason may be interpreted that P2's technical aspect is the highest among participants because P2's design result is based on mainly modular concept, and there are much information related to OS as a result of pursuing shape variety.

c) When there were many GF contents, the concept score was also high. In case of P4, GF was overwhelmingly high and his concept score was the highest among the participants.

d) We predicted that the usability score is related to PE and ME, but there was not much relation shown in them. Our prediction came from an assumption that PE and ME address ergonomic aspect of design so the usability of the product would be high. However, P3 with relatively a good score on usability showed very little amount of information.

4.4. DESIGN PROCESS RESULT

Analysis was done on coded data obtained through 7 design activities in each time period and informal statements. The detailed process was divided into three phases: (1) Problem understanding phase which includes understand and define, (2) Idea generation phase which involves generate and judge, and (3) Design elaboration phase having evaluate and refine steps.

4.4.1. OVERVIEW OF DESIGNER'S PROCESS PATTERN

Design data coded from the process aspect are shown in Figure 3 where the level of activities in each process step is indicated by colors: the darker, the more activities. The horizontal axis indicates the time progression stages.

a) Participant 1: Generally activities were allocated adequately according to the passage of time stages and activities increased in latter part of the process. During the Problem Understand Phase, P1's activities were found steadily from the beginning to a little after the midpoint stage. The activities of Idea Generation Phase were presented after the mid stage of the process. Especially in the Elaboration Design Phase, P1's activities were more vigorous as compared to other participants halfway passed in the phase. Informal Remarks happened in the beginning and the mid stage.

b) Participant 2: Much of P2's vigorous activities were presented in the beginning stage and tendency of frequency in his activities decreased in the latter stage. In Problem Understanding Phase activities were occurred only in the beginning phase. During Idea Generation Phase infrequent activities occurred in the beginning and middle part, and stopped soon after. For Elaboration Design Phase, activities started in the beginning irregularly. Informal Remarks happened in beginning and middle stage.

c) Participant 3: Activities occurred mostly in the middle stage and not many different of activities are shown in the latter phase. In Problem

Understanding Phase activities happened from the beginning until the midpoint and activities occurred vigorously in the halfway of Idea Generation Phase. Only small numbers of activities were shown after the middle part of Elaborate Design Phase. Informal Remarks steadily occurred throughout the whole process.

d) Participant 4: Much of his activities occurred in the beginning stage and for Problem Understanding Phase, activities vigorously occurred from the beginning until the middle stage. Noticeably, the occurrences of activities were presented busily and consistently from the beginning to the ending step of Idea Generation Phase. Also not many different activities occurred in the end phase of Elaborate Design Phase. Informal Remarks were very seldom made.

4.4.2. Process Pattern in Each Phase

Even though defining a standardized design process pattern is difficult, a desirable process pattern can be defined by the stages of process performing appropriate activities in sequence.

P1's design process seems to follow this pattern as shown in Figure 3. In case of other three designers' patterns, however, their patterns also have significance due to the following reason. Overall design process of P2, P3, and P4 appears to oscillate between problem and solution rather than one-way process of first defining the problem and then searching the solution. This result is similar to the study of Cross (1997). According to his study, creative designing seems to proceed by oscillating between sub-solution and sub-problem areas, as well as by decomposing the problem and by combining sub-solutions.

4.4.3. Design Process and PCMT

No significant difference has been found in design process pattern in terms of the types of PCMT. As a whole, the problem solving process of four designers showed similar patterns which took the same r oute from the phase of problem-understanding to problem-solving. The fact that all four participants are trained design experts with more than five years of design practice could account for this result.

In case of P3, whose dominant mode is organizing creativity, the fourth step (D4) 'Judge ideas and context' was of great quantity and the frequency of informal remark (A1) was high. This result means that P3 focused on the analysis of a problem in problem solving process and he had a great deal of confirmation regarding the procedure and process of problem-solving. It is somewhat associated with organizing creativity traits.

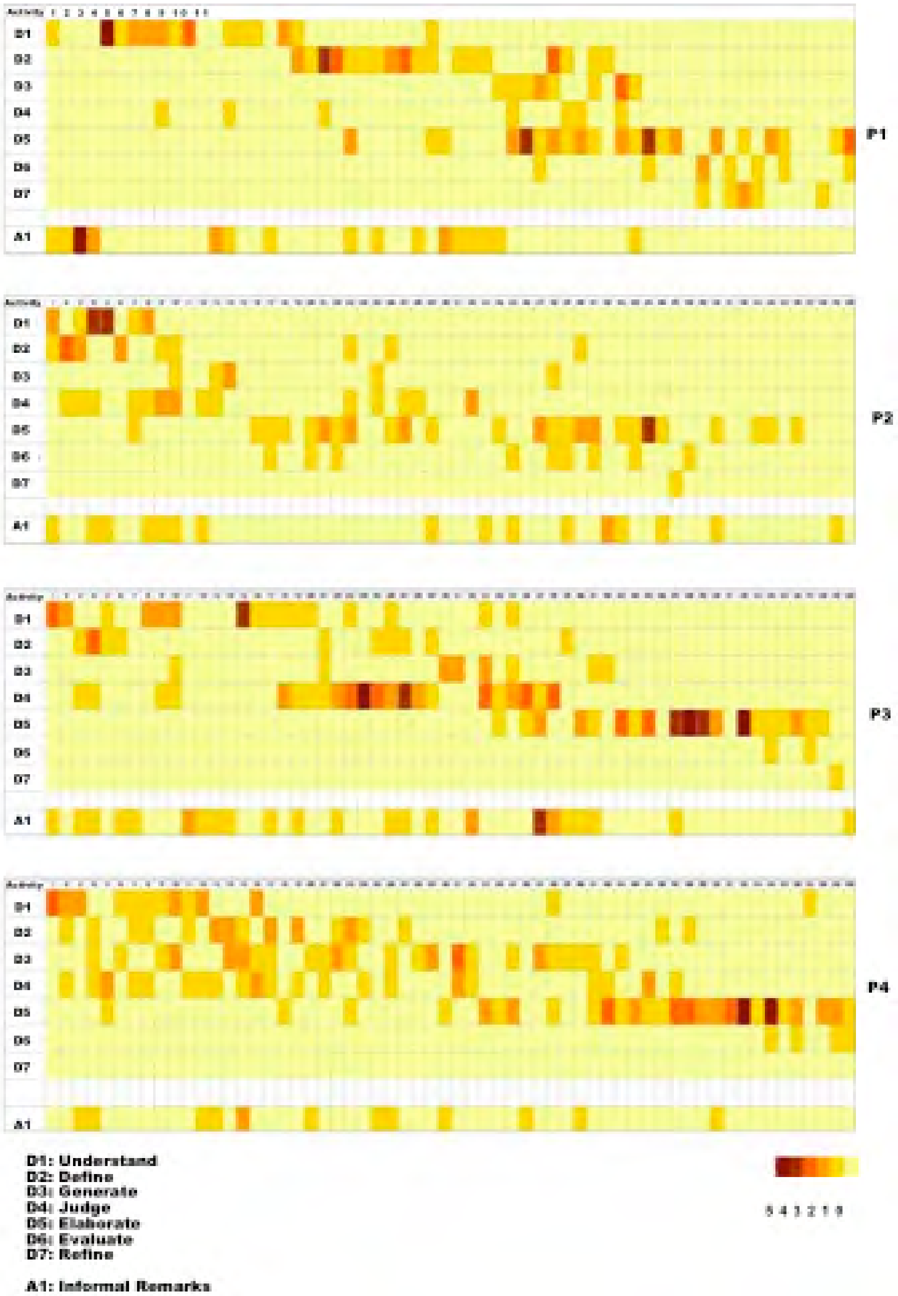


Figure 3. Designer's Activities in Design Process

P4 who has teamwork creativity mode spared more time for problem-understanding stages than other participants, and in this phase he took 'external knowledge (EK)' among design information into great consideration (as identified in Figure 2). In this respect, he might understand and define problem by considering users' physical situations, psychological states, and social contexts. It may coincide with the traits of extroverted feeling creativity mode.

4.4.4. Process and Solution Quality Score

Comparing process-based coding data and solution qualities, the following observations could be obtained.

a) In the relation between process and solution quality, we could observe that an adequate distribution of activities throughout all the processes may be necessary to bring out a good solution. For instance, in case of P1, who scored the highest in the solution score, the frequency of his design activities occurred evenly over all the steps of the process. In case of P4, whose solution received second highest score, though his activities were vigorous in the beginning compared to P1, his activity pattern presents relatively even distribution.

b) Problem Understanding Phase: Participants P1, P3, and P4 who showed high activities in problem understanding phase received high concept scores, while P2 who showed low activity in this phase gained low total and concept scores. As a result, we could identify that problem understanding is very important.

c) Idea Generation Phase: P2 who showed relatively low activities in this phase received low score in functional utility, while P4 whose activities were vigorous in this phase gained high scores on concept and aesthetics. In P3, activities associated with idea judgment were exceptionally high.

d) Design Elaboration Phase: P1, whose solution gained the highest score, did many design activities oscillating through the three steps of the design elaboration phase. P2's activity was not well focused in the final stages of the process and his solution scored the lowest.

4.5. RELATIONS BETWEEN DESIGN INFORMATION AND PROCESS

Comparing the data from the two dual coding schemes together, observations on relation between design information and design process could be obtained. The design information used and mentioned as the design task proceeded is shown in Figure 4. From Figure 3 and Figure 4, the following relations could be observed.

EK appears relatively in the beginning stages of the design process. Note that P4's high activities in the Understand and the Define in relation to strong appearance of EK. IN design information category and the Judge part of the process happen almost concurrently. Note that the judge process and the intent information occurred together in P3. OS and CS are related to the shape of products and they mainly take parts in dealing with the specific shape of products. Hence the two categories are presented in the elaboration design process. CS occurring after OS means that CS is relevant to specific shape of the design. TF is related to the latter process concerned with concretization of design and evaluation. P1 and P3 show these characteristics and P2 starts this activity in the early phase and continues until the latter part. The TF activity of P4 is not significant.

5. Summary and Conclusion

In this study, we encoded the design information and process for expert designers with two complementary coding schemes based on design process and information contents. In addition, we explored the relation between designer's cognitive personality and design process.

Concerning the design information, the frequency of information in expert designer formulates a regular pattern except a few cases. It seemed that the more design contents about context, external knowledge, and general feature are used, the more unique design concepts are made.

Regarding design process, an adequate distribution of activities in process may be necessary to bring out a good solution. The design solution scores varied according to the degree of activities' distribution in problem understanding phase, idea generation phase and design elaboration phase.

Regarding personal creativity modes, not much of differences in that design activity were observed. Only a few relations between designer's personality and design activity were observed. Two designers showed some association with their design process and design information. Feeling oriented personal cognitive characteristics as observed in P4 resulted in rich uses of external knowledge and general features and emphasis on problem understanding and early idea generation phases rather than elaboration phase. Organizing creativity mode revealed by P3 could be associated with rich intent information category that includes process management issues.

As cognitive process may be influenced by a variety of factors such as personal cognitive ability, experiences, expertise and environment, further research to understand the relations between design process and various variables is needed. Investigation on the differences between novice designers and expert designers as reflected in protocol data based on design information and design process coding schemes is to be done to understand more detailed design cognitive processes. Also study on the relation between design process and personal creativity modes for novice designers is to be done to examine whether the influence of personal cognitive style on design process varies according to the degree of expertise or domain experience. Also, how personal process patterns observed through this protocol analysis can be utilized in composing design team will be investigated.

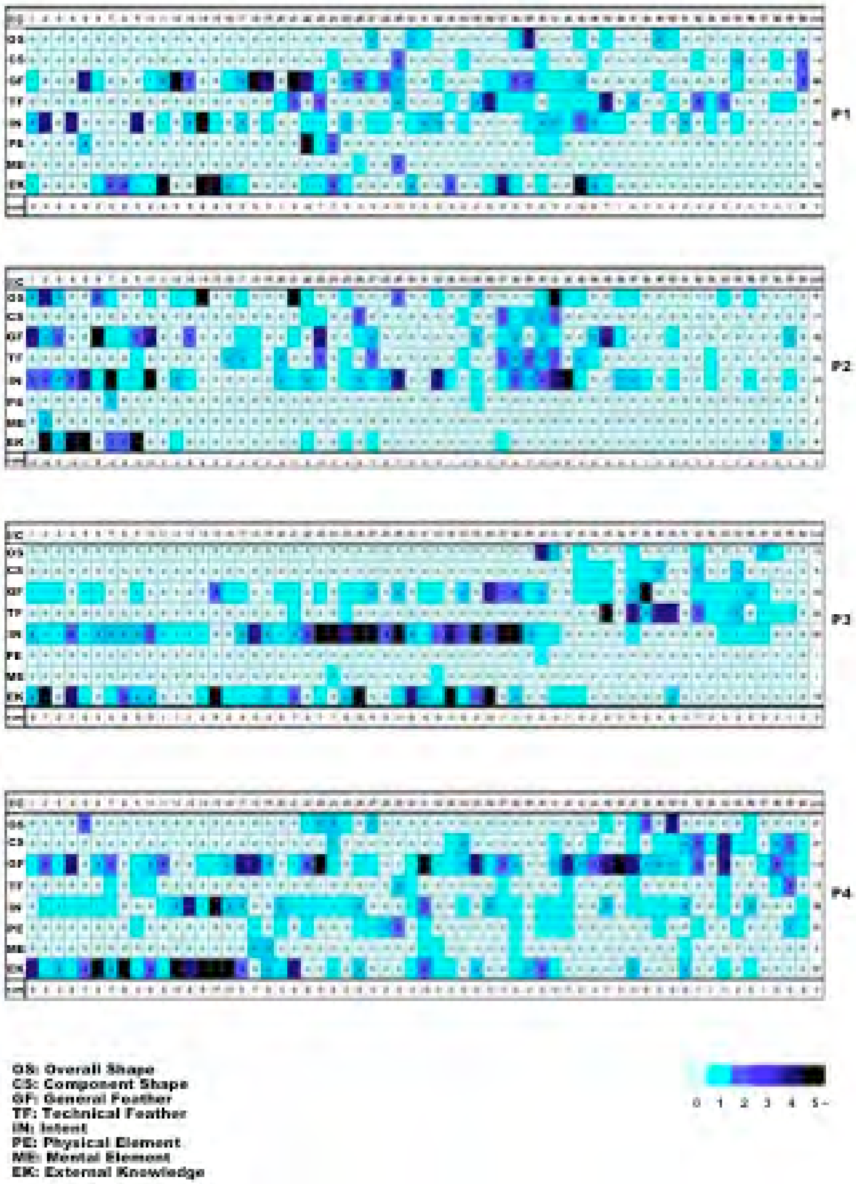


Figure 4. Flow of Each Information Category

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THE NATURE OF CREATIVITY IN DESIGN

Factors for assessing individual creativity

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Abstract. This study focused on the definition of creativity in design problem solving. The purpose was to examine the possibility of grounding the definition of creativity in design in parameters that may be assessed objectively. In this research creativity in design was characterized by a number of factors dealing with fluency, flexibility, elaboration, and innovation, as well as aesthetic skills in design representation, fulfillment of design requirements, reference to context, and usefulness. Results showed that usefulness and fulfillment of design requirements were the most dominant factors in the assessment of creativity in design, followed by innovation in the second place, and finally by fluency and flexibility. Elaboration and reference to context were found to be relatively weaker contributors to creativity.

1. Introduction

Design problems, and architectural problems in particular are ideal contexts to study and assess creativity. A major reason is that these kinds of problems are ill-defined, non-routine, extremely complex and unique (e.g., Reitman, 1964; Rittel and Melving, 1984; Simon, 1984). Since they cannot be solved in line with any clear problem solving procedure, they do not allow the application of known operators or algorithms to arrive at a successful solution. These are strong reasons infer that successful design problem solving requires not only developed skills but also a high level of creativity.

Despite the fundamental importance of creativity in design, issues concerned with the definition and assessment of creativity in design problem solving have not been properly addressed. There have been hardly any theoretically all-inclusive approaches to this subject, and almost not empirical studies supporting them. Some investigations on design creativity have been studying issues concerned with the designer, and a few dealt with the design process. However, a theoretical framework for the assessment of creative design processes and solutions have not been adequately addressed in the agenda of design investigators. For the most part, creativity in design is assessed as a comprehensive or general evaluation, normally based on common shared views, conformity, or agreement of experts. But the criteria and methods applied to carry out the assessment of design outcomes remains subjective and vague.

The present approach suggests a method for grounding the definition of design creativity according to variables that can be evaluated objectively. In this research, creativity in design is characterized by a number of factors dealing with fluency, flexibility, elaboration, and innovation, (e.g., Guildford, 1981) as well as aesthetic skills in design representation, fulfillment of design requirements, reference to context, and usefulness. These factors are considered as a major theoretical basis to assess individual creativity in architectural design. What we want to verify is the relative influence of each of them in design creativity.

A brief literature review about creativity, and design creativity is first presented. Then an empirical research about the factors of design creativity is carried out. Quantitative results obtained from a design problem by architectural students are assessed. Main conclusions are finally presented. Surprisingly, 'practicality in design' was the most dominant factor characterizing creativity. 'Innovation in design' generally considered as the bedrock of creativity, resulted to be only the second most salient factor. The weakest factor was 'dynamism of design' representing the variables of fluency and flexibility.

2. Creativity

Creativity is often defined in very general terms. For example, creativity is seen as one of the key parameters of intelligence that distinguishes us from the rest of the animal kingdom (Goldenburg and Mazursky, 2002). Creativity is known as the capacity to express unusual thoughts, generate insightful judgments, change our culture in some critical way, make important discoveries, and experience the world in fresh and original ways (Csikszentmihalyi, 1997). Furthermore, it is believed to be a human ability that can help to improve routine processes such as thinking and doing (Coyne, 1997). Thus, a physician, an artist, or a designer can be seen as creative when they are able to produce outstanding outcomes

Creativity is also referred as the act of generating or recognizing novel ideas, alternatives, or possibilities that may be useful in solving problems

(Franken 2001).In order to be creative, people need to be able to perceive situations in new ways or from a different perspective, and to generate new possibilities or new alternatives. De Bono (1977) defined creative thinking as the capacity to solve problems through the exploration of multiple alternatives and a variety of approaches associated with unorthodox methods that can be used for modifying conceptions and producing new ones. However, according to Weisberg (1993) novelty does not suffice for considering a product as creative. Some kind of value is also needed, or at least suitability for the demands of the situation. Therefore, creativity has to do with the capacity to produce novel and valuable products. According to Frascara (2004) creativity can be also defined as the ability to conceive unexpected solutions to apparently insoluble problems. In actual practice creativity in individuals is assessed in terms of four factors that have been defined and operationalized by Guilford (1981) and others (Torrance 1974). These four factors are fluency (defined as the total number of relevant responses), flexibility (defined as the different categories of relevant responses), elaboration (defined as amount of detail in the responses) and originality (defined as the statistical rarity of the responses). In the present study these factors will be applied for the evaluation of creativity in design.

2.1. CREATIVITY IN DESIGN

Creativity is a fundamental component of design that can be characterized in terms of a variety of aspects. Creativity in design has been examined with respect to the designer. In a past study on architectural design and creativity Mackinnon (1965) observed that while most creative designers tried to reach an artistic standard of excellence, the least creative group only tried to comply with general standards of the architectural profession. In another investigation carried out by Hanna and Barber (2001) creativity in design was defined by the capacity to take risks to challenge the unknown. Moreover, creative designers were found to have: strong motivation to achieve individual goals, verbal fluency, playfulness, spontaneity, freedom of judgment, flexibility to tackle a problem from different angles, higher than average intelligence, a large variety of interests that extend far beyond the problem domain, a definite need to be original, and eagerness to succeed in their disciplines.

Creativity in design has been examined also in relation to the design process. In line with what was claimed by Weisberg (1993), Gero (2000) suggested that creativity in non-routine design processes has to do not only with novelty, but also with the act of generating valuable and unexpected solutions. Moreover, Gero et al (1988) noted that creativity in design is about the exploration of possible solutions extending the designer's own knowledge. The exploration of a variety of design alternatives contributes to broaden the range of design ideas considered in the conceptual design stage. While the designer tries to expand the range of candidate solutions, the more concepts are examined, the better possibilities to develop satisfactory solutions (e.g., Cross, 1997; Lawson and Loke, 1997; Pugh, 1991; Roozenburg, 1995. In another research carried out in the design studio, Goldschmidt and Tatsa (2005) investigated how different kind of ideas influences the design process, and which ideas can be considered as good ideas. A main finding was that a body of richly interrelated good ideas constitutes the essence for creative and innovative design processes. Candy and Edmonds (1996) showed that innovative design consisted in an exploratory activity characterized by non-routine thinking. The ability to perceive a problem as a whole rather than in details, expertise in the knowledge of the field, the capacity to make abstractions and establish associations between different domains, as well as the consideration of a design problem as a whole rather than as small details were identified as determinant factors of the creativity process.

While a major concern of some research studies is the definition of design creativity, the promotion of creativity in design, or the study of the personality of designers, not many investigations are dealing with an objective assessment of creative design. In regard to this, a major question to be addressed is the way in which creativity is evaluated (Christiaans, 2002). In particular, what are the methods and what is the criteria applied for evaluating design processes, and design outcomes. In most cases, creativity is assessed in terms of a global evaluation usually carried out by design experts. The major shortcomings of this procedure are obvious: first, evaluation is essentially subjective; secondly, it is difficult to determine who is a legitimate evaluator; and thirdly, there is neither a basis for checking or controlling the evaluations, nor a procedure for establishing on which criteria evaluations are based.

An illustrative example of this is the evaluation of students' projects made by design studio teachers at the end of the academic year. Although teachers may agree on the quality of a design project, what is difficult to establish and control is the method and the criteria on which such assessments are supposed to be based.

3. Research Goals

The four factors used by Guildford (1981) (fluency, flexibility, elaboration, and originality) represent an important and commonly used framework for an objective evaluation of individual creativity in various domains, including design. However, since the objective of this work was to assess individual creativity in architectural design (referring to both the design process and the design output), we found it necessary to consider four variables in addition to Guildford's creativity factors These comprised: reference of the design to the physical context, which defined in fact the problem domain of the design task; mastery of aesthetic skills for design representation (e.g. Christiaans 2002), functionality, also termed usefulness (e.g., Franken, 2001), and extent of dealing with the actual design requirements (e.g. Weisberg 1993; Eckert et al 1999).

An explanation for the inclusion of the variable of reference to the context may be required at this point. The physical environment is the locus for establishing a dialogue between the design and its immediate context. Miss-considering this important component is at least as problematic as overlooking basic design constraints and requirements. In the domain of architecture, a design cannot be considered as successful or creative if it does not manage to establish a strong relationship with the environment where it is situated.

The first goal of this research was to examine whether expertise judgment of creativity in design is a reliable and valid method of assessment. The second goal was to learn about the relative importance of each of the proposed factors, and. the relative level of their representation in architectural design creativity.

4. Method

The participants were 52 students of architecture, in the first to fifth year of studies. They were provided with ten A3 numbered sheets of paper, and asked to use them serially. In addition students were given a task sheet containing general instructions, a schematic map of the area (See Figure 1), and were requested to solve and present graphically their solutions to the design problem.

The task consisted in the design of a small museum for promoting the cultural life of a little town. The museum contained basic functions such as a gallery for the display of pictures and posters, a gallery for sculptures, a room for lectures and seminars, a room for administrative tasks, a coffee-shop, and services. A major requirement of the design problem was to provide a creative design solution that would consider the critical relationships between an old Town Hall of over 100 years old, and a natural park. asked to present the final design together with all the material produced during the different stages of the design process. Despite time constraints of the design session, students were required to produce a qualitative and creative design solution to the maximum possible extent. The design session lasted approximately two hours.

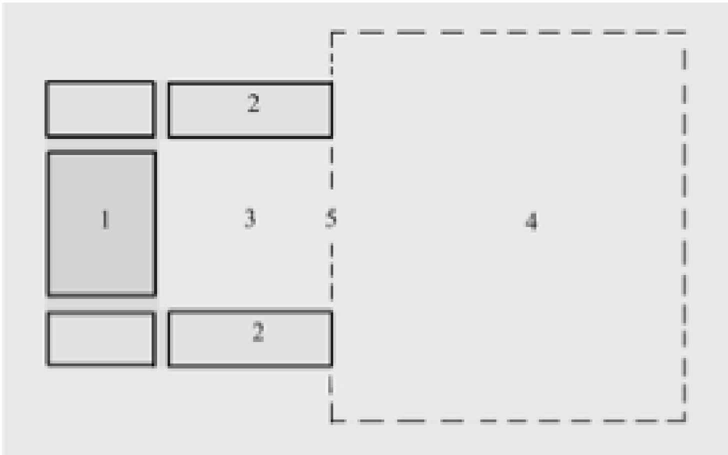


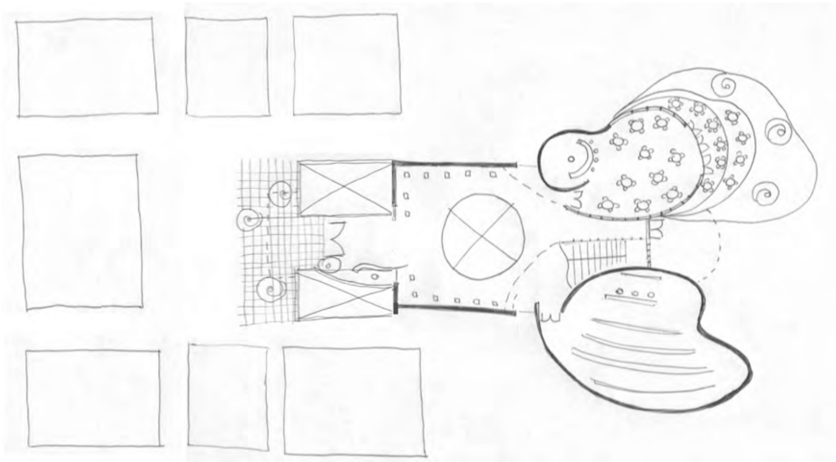
Figure 1. Schematic map representing the urban context provided in the design task. 1. Town Hall; 2. Dwellings; 3. Square; 4. Park; 5. Area available for the design of the museum

5. Example of a design solution by a student

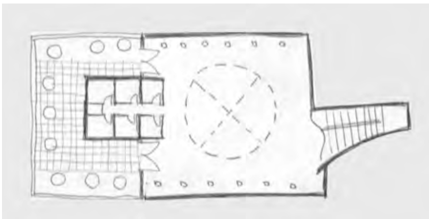
Figure 2 illustrates an example of a solution to the museum problem by one of the students that participated in the design task. In a debriefing session carried out at the end of the task, the student commented that the design idea emerged while thinking in the slogan 'culture for everybody'. This led to the concept of a museum open to all citizens and passing through pedestrians, including those that did not intend to visit the museum. On the other hand, the museum should serve to the purpose of enhancing the urban image of the area, and establishing a strong relationship between the square and the park. The design concept was materialized by developing an internal passage open to all the people, which enabled a natural connection between the Town Hall square, the museum, and the park.

6. Results

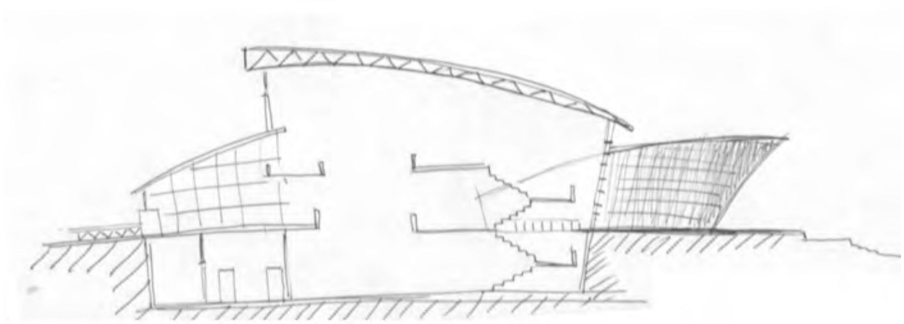
The analysis of the experts' evaluations proceeded in three steps. The first step consisted in checking the degree of correspondence between the four architects in regard to each criterion separately. This was done in terms of a reliability procedure, whereby the scores of the four architects were considered as items in a scale. Table 1 (column 4) shows that the reliability coefficients were in each case very high, which indicates that it is legitimate to combine the scores assigned by the referees for each individual participant in each of the variables. Accordingly, means were computed across the four assessments for each variable for each participant.



(a)



(b)



(c)

Figure 2. Example of a solution for the museum proposed by a student. (a) Ground floor; (b) underground floor; (c) section.

Next, interrelations between different criteria for the same variable were checked in order to examine the possibility of combining these criteria when they referred to the same variable. Hence, the two criteria of fluency were combined because they correlated .618, and the four criteria of usefulness were combined because they correlated .912. Thus, the list of variables was reduced to 8 variables. The third step consisted in applying factor analysis to the 8 different variables (See Table 2). Three valid factors resulted, as indicated by their eigenvalues (>1.00) and the percents of variance for which they account (>5.00%). Also the graph of the scree test (See Figure 3) shows that there is a remarkable decline of the eigenvalues of the extracted factors from the fourth factor onward, which illustrates the stability of the first three factors and the statistical justification for considering only these three factors.

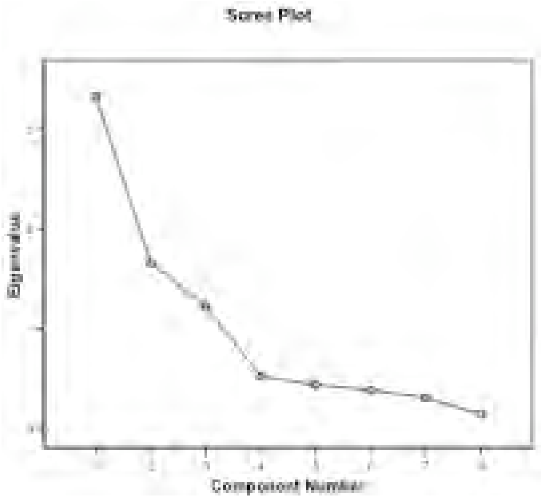


Figure 3. Scree test illustrating the eight design factors as indicated by their eigenvalues.

The first factor accounts for 41.60% of the variance and has high saturations on the variables of usefulness and fulfilling demands of task. Hence, the first factor was labeled 'practicality in design'. The second factor accounts for 20.76% of the variance and has high saturations on innovation and mastery of skills concerned with design aesthetics. Hence, the second factor was labeled 'innovation in design'. The third factor is the weakest. It accounts only for 15.29% of the variance, and has high saturations on fluency and flexibility. In view of the role of fluency and flexibility in the dynamic processes of designing, it seemed justified to label this factor as 'dynamism in designing'

Since saturations in the range of .50 to .70 may be interpreted as indicating potentially medium contributions, it is of interest to note the variable of elaboration that contributes both to the first and the second factor, and the variable of reference to the physical context that contributes to the second factor.

The numbers in the cells are saturations of the variables on each of the factors. The highest saturations that are considered for defining the factor are typed in bold.[1]

6. Conclusions

This study provided a framework for grounding the definition of creativity in general, and in architectural design in particular. Eight variables were used for assessing individual creativity in design. In addition to the four standard variables dealing with innovation, fluency, flexibility and elaboration proposed by Guilford (1981), we included four additional ones referring to mastery of aesthetic skills for design representation, usefulness, fulfilling design requirements, and consideration of the provided physical context.

The high degree of correspondence found between the four referees that evaluated the design outputs confirmed that human judgment of creativity in design is a reliable and valid method of assessment. This conclusion holds at least insofar as the evaluation is carried out by expert designers, using variables defined by objective criteria. Furthermore, the results showed that the most dominant factor characterizing creativity in design is 'practicality in design' representing the variables of usefulness of the design and extent of fulfilling the design task requirements. Remarkably, neither of these variables was considered by Guildford (1981) in assessing individual creativity. Another surprising finding is that the factor of 'innovation in design', representing the originality of the design and the mastery of skills concerned with the aesthetics of design, turned out to be only the second most salient factor. It is unexpected insofar as innovation is considered commonly as the very core of creativity. It is of interest to note that a strong relationship was found between the variable assessing generation of a creative idea, and the ability needed to represent and communicate this idea graphically. It is proposed that proficiency in the use of representation tools can aid in the generation and development of creative ideas in design.

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[1] The factor analysis was performed according to the principal components rotated varimax procedure after Kaiser normalization. For the purpose of the analysis, fluency was redefined in terms of an index (standardized z-scores) based on the two components of number of pages and number of information units (see table 1), and usefulness was assessed in terms of the overall variable representing usefulness A – D. Thus, the number of included variables was 8 (they are specified in the first column of Table 2)

TABLE 1. Means, standard deviations and reliability coefficients of the variables assessed by the architects

Variable and criteria of assessment used by referees	Mean	Standard Deviation	Reliability (Cronbach's Alpha)
Fluency (No. of filled pages)	6.021	2.14	.997
Fluency (No. of distinct units of information)	14.814	6.94	.979
Flexibility (No. of alternative solutions)	.935	.918	.777
Elaboration (No. of features included in the design, e.g., stairs, thickness of walls; furniture. A total of 20 features presented)	9.041	3.11	.888
Usefulness, functionality A (Clarity of function of each component in the design) [rating on 5-value scale]	2.752	1.179	.808
Usefulness, functionality B (Efficiency of functioning of the design) [rating on 5-value scale]	2.457	.951	.824
Usefulness, functionality C (Availability of all the drawing plans according to the presented drawing sections) [yes/no response]	.33	.422	.652
Usefulness, functionality D (Degree to which the design may be realized in reality) [rating on 5-value scale]	2.67	1.059	.773
Usefulness, functionality: Overall	2.503	.902	.916

Innovation value [rating on 5-value scale]	2.645	1.082	.758
Fulfilling specified design requirements [rating on 5-value scale]	3.67	1.162	.865
Considering context [rating on 5-value scale]	2.562	.854	.839
Mastery skills concerning the aesthetics of the design representation [rating on 5-value scale]	2.69	1.141	.827

As noted, the finding that practicality was a stronger factor than innovation is surprising. Historically, innovation was taken for granted as the most outstanding element characterizing creativity in general, and design creativity in particular. Findings in this study reinforce what was suggested by Franken (2001) and Weisberg (1993) that creativity is concerned not only with the generation of novel ideas, but also with their usefulness or adequacy for the problem at hand. The emphasis on practicality may be more pronounced in architecture as an art than in other kinds of art that are endowed with much more limited functionality. On the other hand, the ordering of the factors could reflect the approach of our specific sample or the relatively low level of creativity in the participants of this study. Thus, the placement of practicality in the first place and of innovation in the second place could be interpreted as reflecting either the nature of creativity in architecture in general or the characteristic approach of the sample of participants in the study.

Finally the weakest factor in the context of our study turned out to be 'dynamism of designing' representing the variables of fluency and flexibility. One reason for the relative weakness of this factor may be that designs do not include enough indications about the processes of designing. Another reason could be the nature of the sample. Flexibility requires a particular capability to analyze a problem from a variety of viewpoints. It is possible that students did not explore enough alternatives or a same alternative from different perspectives before producing the final design.

TABLE 2. Results of a factor analysis on the variables assessed by the architects[2]

Variables	Factor 1	Factor 2	Factor 3
Fulfilling specified design requirements	**.925**	.044	.037
Usefulness	**.924**	.232	-.006
Innovation	-.130	**.870**	.018
Mastery skills concerning the aesthetics of the design representation.	.434	**.759**	-.044
Reference of the design to physical contex	.281	.690	.361
Elaboration	.543	.626	-.044
Fluency	-.001	-.045	**.869**
Flexibility	-.005	.145	**.868**
Eigenvalue of factor	3.328	1.661	1.223
Per cent of variance accounted for by factor	41.603	20.763	15.289

Furthermore, a limited role assigned to flexibility may point to the fact that there was a tendency to engage fast in the solving of a unique design solution, before exploring enough alternatives. Hence, the students were not fluent enough to produce a considerable amount of graphic information. A third reason could have been time constraints assigned to the design task.

Elaboration and reference to the physical context were found to provide more limited contributions to creativity. It is possible that although the graphic design representations produced by students had a high aesthetic value, they were schematic, and as such lacked a satisfactory level of detail

[2] The 5-value scales ranged from low ratings (=1) to high ratings (=5), each level of rating being described verbally

and information. Again, this could be due to time constraints imposed on the task.

In the next phases of this research project, the findings of this study will be validated in further contexts and the interrelations with the evaluations of creativity per se will be explored.

Acknowledgments

Thanks are due to the anonymous judges who contributed with their time to assess the outcomes of the empirical task.

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A COGNITIVE MODEL OF THE ENGINEERING DESIGN MIND

The Case of the X-Leg Platform

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Abstract. Engineers use reasoning to transform knowledge when creating an engineering design. The designer tests the transformed knowledge using models of the design's anticipated functional, behavioral, and physical characteristics. In general, the engineer uses an overarching economic aesthetic criterion to make design judgments and decisions. Most projects require collaboration between designers in a form of distributed cognition. This article describes a model of engineering creativity that abstracts these elements of the designer's cognitive activity at the *cognitive style* level. Using interviews with the designers and the designer's sketches, drawings, and calculations, a cognitive historical case study of a recent historically-creative engineering design is conducted (1) to test and verify the cognitive style model of design, and (2) to shed light on one particular instance of innovative engineering design.

1. Introduction

Current methods for studying design include computational simulations and studies of observable human behavior. Computational simulations can be used to produce novel designs (Koile, 2004); to investigate either the design strategies used by the computer (Cruise and Ayres 2004) or the designers' social interactions (Sosa and Gero, 2004); or to develop computer programs to assist design (Mora, Rivard and Bédard 2004). Studies of observable human behavior include protocol studies (e.g., Ball et al. 1997) and 'design product' studies (e.g., Jaarsveld and van Leeuwen 2005; e.g., Moss, Kotovsky and Cagan 2004).

Historically-creative acts of design, as first identified by Boden (1991), have only rarely been studied (e.g., Cross 2002) for several reasons. First, time limitations restrict problem difficulty in lab studies. Second, lab studies that allow subjects to choose the design problem to be solved are difficult to evaluate. Third, amount of domain knowledge required for historically-creativity design requires experts, who can be difficult to recruit for academic studies. Finally, even when such subjects can be recruited, wide variation in the subjects' knowledge may allow individual differences to obscure group differences.

2. The Cognitive Historical Case Study

The need for a research method which can provide both testability of a theory and ecological validity of the results has led us to develop the *cognitive historical case study* (CHCS) method as developed and used by Dasgupta (1994; 2003; 2005) in the domains of technological, scientific, and artistic creativity.

2.1. ISSUES IN USING THE COGNITIVE-HISTORICAL CASE STUDY APPROACH

Misunderstanding of the purpose of the case study has led to methodological criticisms of the case study as (1) possessing only a single statistical degree of freedom, (2) lacking experimental control, (3) lacking a mechanism to control for experimenter bias, and (4) requiring the researcher to possess extensive domain knowledge.

However, case studies are the preferred method for studying rare events in many domains including physics, astronomy, chemistry, psychology, ecology and medicine, with results used to generalize to a theory rather than to a population of individuals or events. In addition, the CHCS can be used to generate a theory of in individual act of creativity. Thus, the CHCS allows for developing, verifying, or refuting both *nomothetic* models that generalize to universal theories and *ideographic* theories of individual acts (see Wallace 1989).

The use of a historically creative design provides several advantages over laboratory studies. One issue in laboratory studies is the extent to which findings can be generalized to the "real world", or the *ecological validity* of the results. Unlike most laboratory studies of design, the CHCS investigates historically-creative rare events. The subject of a CHCS is chosen from the (theoretical) set of design projects that have been judged historically creative. Thus, the results of the research are ecologically valid *by design*.

2.2. GOAL OF THE COGNITIVE-HISTORICAL CASE STUDY APPROACH

The goal of the CHCS is to use historical research techniques to recreate the context of the complex of cognitive processes that produce the creative product. In related work, Dasgupta (1994) used public records to conduct a historical case study of the design of the Britannia Bridge to test and corroborate his hypothesis law of design. Dasgupta's (2003) later CHCS of Herbert Simon led to the development and testing of his model of multidisciplinary scientific creativity. In this paper we present an ongoing research project that illustrates the application of the method to the study of designers and design cognition.

3. A Cognitive Style Model of Design

Design cognition research has used Newell's (1982) knowledge-level model of cognition as a framework (Sim and Duffy 2003). Newell (1982) characterized a knowledge-level system as an agent that is composed of knowledge, goals, and a body which has the ability to collect and use knowledge. For Newell, an agent symbolically encodes knowledge in a representation so that it can be accessed. Thus, to say an agent 'knows' something means that the agent can use that knowledge to satisfy a goal.

Design has been described at the knowledge level as a set of design definition activities, design generation activities, and design evaluation activities that change the designer's knowledge (Sim and Duffy 2003). At this level, the designer can be characterized as using knowledge to transform design input knowledge into design output knowledge (Sim and Duffy 2003) to satisfy a goal. However, for various reasons we consider this knowledge-level model incomplete. Instead, we propose a model of design at what we call the *cognitive style (CS) level* (Dasgupta 2003) as an abstraction of the cognitive process of design. The CS model incorporates several components that explain how the designer's knowledge is organized and recalled, acquired and used, transformed, and, finally, tested.

3.1. KNOWLEDGE

First, the agent's sensory-perceptual and motor systems collect information that is organized in *cognitive schemas*.

In particular, through both life experience and formal training, the designing agent attends to the functional relationships between system components. The agent learns to ignore surface attributes and abstract functional relationships. In the process, the agent creates mental representations of the abstract functional relationships. That is, the designer creates a schema of a system's *operational principles* that describe how the system works (Dasgupta 1996). These abstract functional cognitive schemas form the basis for a large portion of the engineer's body of knowledge.

The engineer's training refines and reinforces the knowledge organization schemas that are organized around functional relationships. Practical experiments are used to develop theoretical abstractions of the functional relationships in a system. These theoretical abstractions are then applied to other situations which may or may not resemble the cases upon which the theory is based. One example of this progression is the development of a theory of elasticity to explain stresses and strains in metal springs. Later, 'spring theory' was applied to building foundation design to model a foundation as a series of elastic springs. Certainly, metal springs and natural soils share little surface similarities. Their similarity is strictly functional.

Only a small subset of all signals sent in the world are received as information by an agent. That information, moreover, must be encoded as knowledge in order to be used by the agent at some point in the future. That is, the agent is limited to using information that the agent has encoded as knowledge. In this model, the designing agent uses domain and non-domain knowledge, theoretical knowledge, and knowledge of goals to produce potentially useful innovative designs. Thus, the information in the world that the agent attends to and the way that the agent organizes its knowledge are both crucial to design.

3.1.1. Domain Knowledge

Domain experience is that experience obtained in the general field of work to which the innovation pertains. Domain knowledge need not be limited to formal training programs.

3.1.2. Non-Domain Knowledge

General life experience can be a significant part of the designer's knowledge base. Even without theoretical training (as described below) most young adults entering the engineering profession have a general understanding of the effect of placement of a load and member size. Other non-domain experience includes knowledge of solutions to common and uncommon problems. Such experience can be common to most designers or unique to the individual. Unique experience can be obtained through experience in a different culture, hobbies, or non-domain work experience.

3.1.3. Theoretical Knowledge

Theoretical knowledge is considered to be the type of knowledge that is typically included in university engineering training, whether the designer acquires that knowledge from university coursework or from on-the-job training. Included as theoretical knowledge are such things as the theoretical relationship between stress and strain for a particular material and the relationship between a structural member's material composition, shape, and its ability to support load (i.e., the relationship between the member's material composition, moment of inertia, and its theoretical strength).

3.1.4.Knowledge of Goals

Knowledge of important goals is crucial to design success. In fact, some theorists describe *goal-driven behavior* or *goal-seeking* as independent of knowledge. Here, we prefer to model knowledge of important, soluable goals as one category of knowledge that the designer uses in creating an innovative design. A design goal is an objective for the design. A design constraint limits design goals. For example, as earthen levees are made taller in a flood control project, they must also be made wider. Thus, the design is constrained both by the desired height (goal), and the available resources (economic constraints on materials and available land). Essentially, a constraint can be viewed as a goal, albeit a negative one (i.e., a limiting goal).

Innovative design solutions propose a resolution to what we call a "design dilemma". A design dilemma (DD) is present in situations in which two or more design goals (or design constraints) are linked functionally. One common design dilemma is one in which an economical beam must be selected to support a certain load, but due to architectural considerations, the beam is limited in overall depth. In this case, the beam must possess a certain strength, but as its strength primarily results from its depth, limitations on depth in turn limit a potential beam's strength. Normally, this design dilemma is easily solved, but in certain long-span situations, the beam's own weight contributes significantly to the load to be supported. As the beam gets heavier, the load to be supported (which includes its own weight) increases. An innovative solution is required to solve the design dilemma.

3.1.5. Knowledge Change

Sim and Duffy (2003) proposed a generic ontology that describes design activities as *knowledge change* activities. Here, we propose that the designer's knowledge changes as reasoning processes transform the designer's input knowledge into output knowledge.

3.2. KNOWLEDGE TRANSFORMATION: ANALOGICAL REASONING

The CS model includes the processes that transform knowledge (Sim and Duffy 2003). Like creative scientific reasoning (Dunbar 1997), historically-creative design cannot rely exclusively on deductive processes because such creation *by definition* requires reasoning beyond the known. According to Simon (1975), the agent's bounded rationality leads the agent to "satisfice" problem solutions. Here, we propose that undifferentiated conscious and unconscious reasoning processes produce the inferential analogies which link goals to knowledge to produce new knowledge. Although creativity researchers often use distant analogies as examples, Dunbar (1997) has shown that close analogies are more common than distant analogies in scientific creativity. Using the constructs of Forbus, Gentner, and colleagues (Forbus, Gentner and Law 1995; Gentner 1983), the designer can be described as searching for a useful analogy among previously encoded functional abstractions, recalling the functional relationship between elements in the base systems and selecting one as the analogue for reasoning about the target system.

Knowledge and process interact as the designer attempts to satisfy multiple design constraints. Ultimately, some form of *economy* (or *convenience*) governs the design and selection of most engineering systems (for a discussion, see Pye 1978). The agent uses knowledge of previous designs and reasoning about the current problem to determine which of several linked design constraints *governs* the design and must be satisfied *first* to produce a product that can meet the project specifications.

3.3. KNOWLEDGE TESTS

The designer's knowledge must be tested. In order to realize a design, the design process must extend beyond the initial idea generation phase. After preliminary sketches are produced, hypotheses are proposed and tested (Dasgupta 1994) which may lead to a revised design through new analogies or other reasoning strategies. Ultimately, engineering design requires validation by a consumer. Here, the process becomes, by definition, a social interaction where consumers validate the idea by any of the following (in order of increasing 'success'): creating design sketches that the designer judges to be satisfactory, receiving patent approval (recognizing the idea's originality), licensing or selling the patented idea, or realizing a physical instantiation. An idea remains untested until it is validated by others (mentally) and by the real world (physically).

The interacting elements described above (the agent's knowledge, goals, body, emotional drive, and the reasoning process that transforms knowledge) comprise the cognitive style of designers in general and of any one designer in particular. To the extent that designers are alike, they share a common cognitive style. Elements that are unique to the individual create the individual's unique cognitive style. Thus, the CS model is both *nomothetic* and *ideographic.*

3.3.1. Modeling

Models range from mental models to mathematical formulae to full-scale prototypes. A mental model, perhaps in the form of visual mental imagery (Johnson-Laird 1996), is the first representation of a design. The designer can externalize such imagery in several ways, including verbalizing the model, gesturing, or sketching. The externalized mental model may serve as an aid to memory, a design aid to check for interferences, and as an aid for communicating with other designers, clients, and builders.

Sim and Duffy (2003) describe *models* as providing a means to represent some aspect of a design, with models designed to anticipate functional, behavioral, and physical characteristics of the target system. For one design, several different types of models may be used to anticipate different aspects of the design.

3.3.2. Empirical Tests

The eventual test of a design is its fulfillment of its multiple intended functions, which are known as its *specifications*. In general, specifications can be either explicit or implicit.

3.4. AESTHETICS IN JUDGMENT AND DECISION MAKING: THE ROLE OF THE PRODUCER AND THE CONSUMER

Engineering decisions are judgments of a design's satisfaction of a certain engineering aesthetic. This engineering aesthetic can be expressed in many ways; however, all reflect an overarching goal of economy of materials, time or some other important quantity. Thus, engineering designs are selected primarily on the basis of the their economic benefits over other potential designs. However, there is not one single economic criterion. Short term costs, life cycle costs, ease, convenience, and uncertainty all contribute to the perceived economics of a project.

In addition, a model of the designer must incorporate the designer's motivation to identify an important problem, propose a solution, and convince others of the solution's value. Selection of a soluable problem is critical to a design's success.

Finally, the model includes a producer/consumer model of creativity. In this model, both the designer's and the consumer's aesthetic evaluation judges whether a design satisfies the project's specifications. The first consumer of a design is the designer who recognizes the potential value of an idea (Dasgupta 2004). In engineering design, consumers also include design collaborators and clients. Each consumer must share most elements of the CS model of design in order to recognize the value and historical significance of the innovation.

3.5. DISTRIBUTED COGNITION

Dunbar (1997) has documented the advantages of distributed reasoning in generating alternative hypotheses and experiments in modern scientific discovery. For complex design projects, the advantage of using distributed cognition may be in accessing domain and non-domain knowledge of multiple agents. When two or more cognitive agents interact, the collaboration may exploit a division of labor for the design work. In this view, one agent perceives stimuli in the environment (objects, sketches, text, speech, or other sensory stimuli), processes and transforms the agent's knowledge, and returns a result to the environment (likewise as an object, sketch, text, speech, or other sensory stimuli). Many agents may be involved in this process; there is no theoretical limit to the number of agents in such a distributed cognition environment.

4. The Test: The Case of the X-Leg Platform

The proposed test for the CS model is a recent real-world historically-creative engineering design. Two engineers have recently developed an innovative design for deepwater petroleum exploration and production (E&P) platforms in the Gulf of Mexico. (An exact chronology cannot be revealed publicly for patent protection purposes.) At the time design commenced, existing solutions for the problem of deepwater E&P included a variety of floating platform systems, including tension-leg platforms and spar platforms (for a recent discussion, see Leffler, Pattarozzi and Sterling 2003). For such projects, clients select a design based on the economic consequences of multiple criteria, including construction issues, transportation and installation issues, and serviceability issues. Thus, a successful design must satisfy multiple linked constraints without violating the overarching economical constraint. A solution that satisfies one constraint without considering the consequences to other constraints runs the risk of violating the overarching economical constraint – to profitably extract and transport the petroleum product.

As described above, the two engineers and their consulting collaborators can be viewed as interacting agents who comprise a larger cognitive superagent. For large-scale design projects such as offshore petroleum E&P platforms, the sheer amount of domain knowledge required for the design exceeds the capacity of any one individual.

PA, a resident of Houston, Texas, began his career as a research engineer and later spent approximately 30 years working in the offshore petroleum engineering and construction industry. He spent the last three years before his official retirement in 2003 designing products to improve both practical and marketing issues regarding floating platform systems. PA’s design partner, LR, has worked for over 30 years as an engineer in research and development and in the design of innovative mechanical and structural systems.

Recently, PA and LR have been developing a design for an alternative to the tension-leg and spar platforms. Their innovative design, which they have named the “X-Leg Platform”, is shown in Figure 1. Like other innovative design solutions, it proposes a solution to what we call a “design dilemma”. For deepwater platforms, the primary design dilemma is located in the following constraints: (1) the need for a tall floating structure which can satisfactorily support the E&P platform, and (2) the need to construct and transport the structure horizontally for economical and practical reasons.

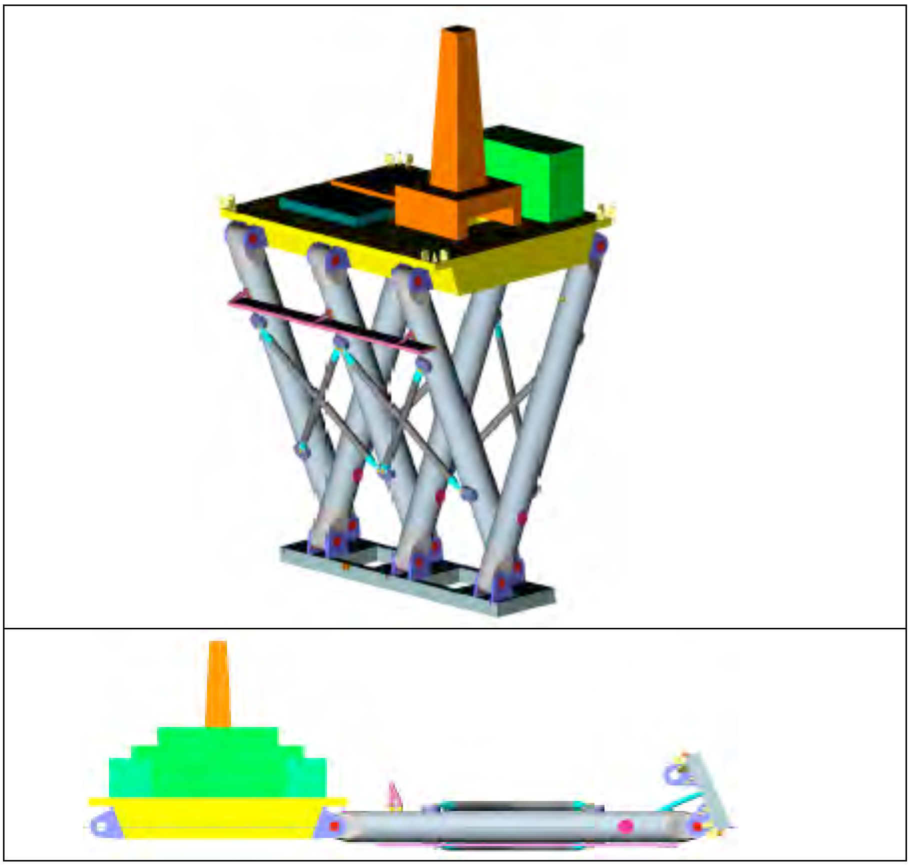

Figure 1. The evolved X-Leg Platform as deployed (top) and in transit (bottom).
(Courtesy X-Leg Platforms, LLC. Patents pending.)

The design created by PA and LR was selected to test the CS model because (1) it is historically-creative; (2) adequate historical records of the development and evolution of the design are available; (3) the designers are available for retrospective interviews; (4) the client evaluators of the design may be available for retrospective interviews; (5) the design is continuing, so that the process of improving the design may be investigated; and, finally, (6) as a physical artifact, the X-Leg Platform is a concrete entity that can be easily understood by intelligent laypersons.

4.1. KNOWLEDGE

4.1.1. Domain Knowledge

Evidence in the interview and the design documents supports the claim that extensive domain knowledge is used in historically-creative design. In the interview, PA and LR discuss their knowledge many concepts in the domain of petroleum E&P platforms, including the following: (1) existing technology for deepwater E&P, including semisubmersible platforms, tension-leg platforms and spar platforms; (2) the economic advantage of constructing large structures horizontally in order to minimize danger and expensive equipment lifts; (3) the economic advantage of floating deepwater platform structures horizontally; (4) the cost, scheduling problems, and overall scale of offshore platform lifts by a derrick barge; (5) the advantages and disadvantages of a 'dry tree' or 'wet tree' design (i.e., platform-mounted equipment vs. subsea equipment); (6) ballasting issues; (7) torsion issues; and (8) wave behavior. The designers often noted that an issue strongly affected the economics of the design, and they frequently described such an issue as "governing" the design, or in LR's words, "we've got a pretty good eye, and uh so we went with a certain size for the amount of buoyancy that we needed and the depth of the heave plate and that sort of thing, to get the behavior [that is needed]".

Each agent contributed different domain knowledge. PA's domain knowledge reflects his knowledge of goals and constraints in the industry (e.g., size and weight of deepwater E&P platform equipment) and construction issues (e.g., economics of construction techniques and ballasting and buoyancy issues).

The evidence for the use of domain knowledge in the design documents includes references to construction, construction logistics, details of design specifications related to operating the platform (i.e., issues relating to well guides, porch, risers, and air lines), ballasting issues, and uprighting issues.

4.1.2. Non-Domain Knowledge

The evidence in the interview and the design documents supports the claim that non-domain knowledge was used in the design of the XLP. First, and perhaps most important, was PA's use of a TV-table as the analogue for his design (discussed in detail in Section 4.2 below). The initial sketch for the XLP closely resembles the proportions of the wooden TV-tables that were in PA's environment (Figure 2). Furthermore, the connection and transformation of the legs from the floating configuration to its final configuration closely resembles the sliding mechanism on a TV-table.

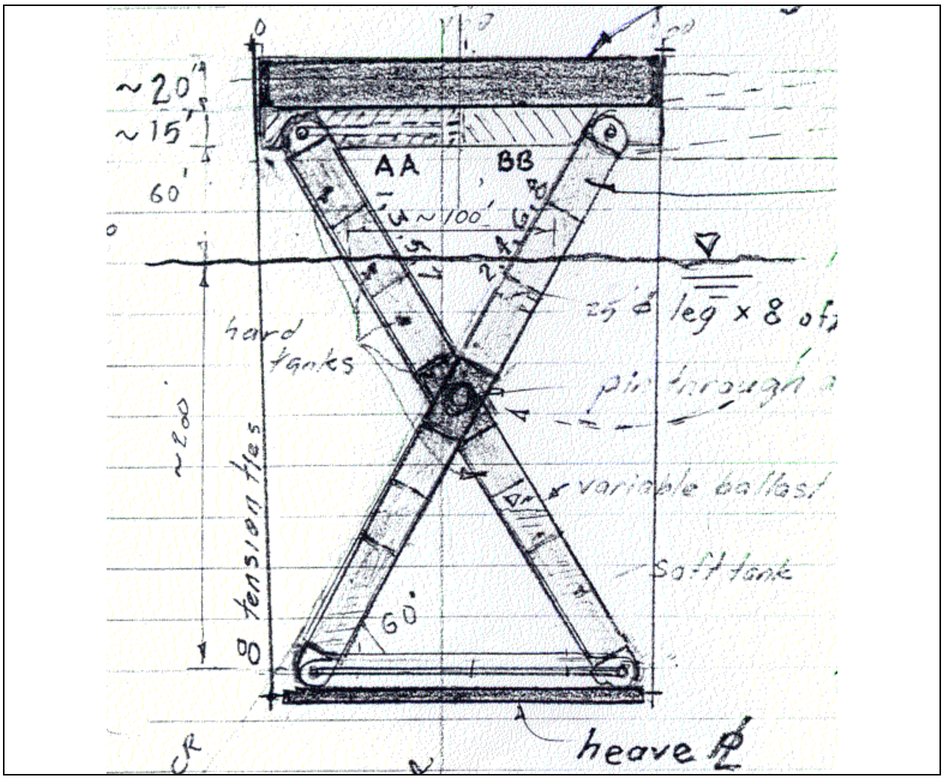

Figure 2. PA's initial elevation sketch of the X-Leg Platform as deployed. (Courtesy X-Leg Platforms, LLC. Patents pending.)

4.1.3. Theoretical Knowledge

The design documents include theoretical mathematical calculations for buoyancy, column buckling, rotation, and hydrodynamic response to wave action.

4.1.4. Knowledge of Goals

One important type of knowledge for innovative design is knowledge of important, viable domain goals. In the interview, PA and LR refer repeatedly to economic goals in terms of the construction cost of the XLP or the "ease" of constructing the structure horizontally near the ground.

Goals in conflict present a *design dilemma* to the engineer. PA recognized an important design dilemma when he described the need for a tall vertical structure and the draft limitations of the Gulf Coast ports, explaining, "…but how in the world do you build something like that and haul it out of water that's, maximum, 45 ft. deep." His solution to this design dilemma provides the primary innovation in his design. From this solution emerged the second major innovation of the XLP design, the connection of the platform to the supporting legs during transportation.

4.1.5. Knowledge Change

As noted above, reasoning transforms the designer's input knowledge into output knowledge. The first sketches show a TV-table inspired slide mechanism for the deployment of the platform's legs. Later, PA abandoned that design for non-sliding pin-connected legs. Much later, he revised the design again so that the legs attach to the side of the platform rather than the underside of the platform. Each version of the design represents a change in the designer's knowledge. According to PA, attaching the legs to the side of the platform was not considered until he recognized the multiple problems in an under-platform attachment.

A second example of knowledge change in the design process resulted when PA and LR gave a preliminary XLP design to a naval architecture firm for analysis. The naval architects determined that the heave plate at the bottom of the XLP could be much smaller than PA and LR had designed it. The naval architects communicated this new knowledge to PA and LR. The designers found this to be a "radical revelation" that changed their own knowledge of the structure.

4.2. KNOWLEDGE TRANSFORMATION: ANALOGICAL REASONING

Analogy is one of the major reasoning strategies by which the designer's input knowledge is transformed into output knowledge. The rare case in which a designer appears to use a formal 'if-then' logical statement can be viewed as a 'special case' of analogy in which there is a near-perfect match between elements in the target system and conceptual elements in the base system. Even statements that may appear to be formal 'if-then' statements include some amount of non-perfect match. For example, PA's 'if-then' statements reflect alternative designs, rather than certainties of a particular design. In general, the uncertainty present in all design prevents the frequent use of 'if-then' reasoning. In fact, logical reasoning of this form can *only* be used if there is a near-perfect match of target and base. The near-perfect match in formal logical statements can be viewed as the *closest* of all close analogies.

In order of distance, the next-closest analogy is a *within-domain analogy*. Within-domain analogy is the subtle transfer of knowledge from an existing project as the base system to a target system (the new design). (See Section 4.3.2 below for a discussion of empirical design tests.) PA describes his reasoning about the design, "I mean, after all, what is this, it's essentially a semisubmersible with inclined legs." Later, as he describes the design, "We have a big heave plate down there. Well, the EDP [*extendible draft platform*] has a heave plate. We've got columns; float out in shallow – all of these things are just slight changes to things we know work." Within-domain analogy can be important to verifying the technical feasibility of a project, but is unlikely to be the source of important creative advances.

More distant is *outside-domain analogy*. In outside-domain analogy, the base system for the analogy is any form of non-domain knowledge such as related-domain knowledge or life experience knowledge. The most striking example of outside-domain analogy in the XLP project is PA's initial analogy of a TV-table as the functional equivalent of a floating platform system. While matched on elements such as 'low horizontal profile' and 'transforms into high vertical profile', the two systems are not matched on elements such as 'construction material' (wood vs. steel) or 'operating environment' (home vs. ocean), or 'means of support' (stands on four legs vs. buoyant system). The evidence to support the claim that PA used a TV-table analogy includes PA's verbal statements and his initial, dated sketch. The sketch strongly resembles the concept and proportions of a TV-table. Alternatively, there exists the possibility that his analogy is incorrect, either intentionally or unintentionally. Here, we will argue that the sketch provides adequate evidence that a TV-table is the analogue for the floating platform design based on its proportions and the means of attachment for the legs. The initial sketch does *not* resemble other folding structures such as an ironing board, umbrella, or a folding chair. It remains possible that PA is misrepresenting the source of his idea (i.e., that perhaps it was someone else's idea). If that were the case (and we must reiterate that we have no reason to think that *is* the case), the evidence at hand would still support the use of a TV-table analogy. However, the cognition would simply be *more* distributed than we have described here, including an additional individual.

A second example of outside-domain analogy concerns a relatively minor design element that the PA visualizes as working like a moveable clothesline. In this case he explains, "So, if you had a continuous loop, you could – kind of like a clothesline, you know, you would haul this across just like it was clothes".

One interesting special case of outside-domain analogy is the *anthropomorphizing analogy*. In anthropomorphic analogy, the target system is compared functionally to a human or other animal system. In these cases, the designers used statements such as, "He said he eliminated it completely and it hardly could tell the difference" or structural systems "always are trying to fall over".

4.3. KNOWLEDGE TESTS

4.3.1. Modeling

Several models were produced during development of the XLP design. First, PA's initial concept of a folding platform is a mental model. He reports that almost immediately he produced a sketch, which is the first externalized representation of the mental model. Later, PA reported using his wooden TV-tables as physical models of a folding platform. Upon sharing his idea with LR, LR refined PA's sketches into more detailed drawings. Throughout, calculations were used to model the expected buoyancy of the system and the response of the legs to compressive load (i.e., column buckling). At one point, naval architectures used computerized mathematical models to predict one aspect of the system's behavior in a design storm. Finally, PA and LR have recently manufactured a scaled-down physical model of the XLP in order to demonstrate the platform's deployment mechanism to potential clients. Interestingly, at this point the physical model will not be used to model the hydrodynamic properties of the platform. A future physical model would be required to test the platform's hydrodynamic response.

4.3.2. Empirical Tests

The XLP has not yet been built; hence it has not had a full empirical test. However, other completed projects operating in a similar real-world environment can provide a close analogy to partially validate for a new design. PA used several close analogy tests in his design, including his comparison of the XLP to a "semisubmersible with inclined legs", as discussed above. In addition, he reports that a potential client used a similar close analogy to validate the design.

4.4. AESTHETICS IN JUDGMENT AND DECISION MAKING: THE ROLE OF THE PRODUCER AND THE CONSUMER

4.4.1. The Role of Aesthetics in Engineering Judgment and Decision Making

In design, PA and LR made several judgments about the value of a particular design element. One elements was described as "a whole lot better", and another as a "bad idea". PA expresses his search for "something clever" to solve a transportation problem. He recognizes the value of finding an unusual solution to a problem.

The designers frequently described making aesthetic judgments about the evolving design. In describing one detail of the design, PA describes his uncertainty about potential alternative designs, concluding, "I don't know [whether this is the best way to do it]. It looks nice." At another time, he admits that there his proposed solution to one minor issue is "probably not the best way".

One important aspect of the designer's aesthetic judgment is economic considerations. As PA describes one aspect of his design, "Where, if you could have finished it inshore, it would be safer, cheaper, faster; everything's better." Likewise, smaller (therefore lighter) components are valued as being advantageous in construction.

4.4.2. The Producer/Consumer Model of Design

At press time, several consumers have validated the historical creativity of the XLP design. First, PA initially recognized that his idea would likely be an improvement over existing alternative designs. Then, his partner PA recognized the value of the design. Patent officers have established the idea's originality. Over a period of time, PA and LR presented the idea to several potential clients. One potential client, in particular, has responded positively to the idea. In the near future, the design will be presented to other consumers, thus providing the potential for further validation of the design's advantages.

4.5. DISTRIBUTED COGNITION

The design of the XLP required several cognitive agents working together. At the least, the evidence as presented by PA and LR shows the interaction of PA, LR, and a naval architecture consulting firm. In addition, cognition can be considered to be distributed to the engineers who devised the theoretical tools that the designers used, such as the mathematical models of the concept of 'waterplane moment of inertia' and the computer model used by the naval architects.

Thus, the evidence supports the claim that engineering design (at least in the case of large, complex projects) requires the use of a network of distributed cognitive agents.

5. Discussion

In this ongoing research, we have used design sketches, calculations, models, retrospective verbal protocol data from interviews of the designers to test our proposed CS model of design.

Here we have proposed a model of engineering design at a particular level of abstraction, the case study model of the engineering design mind. The work serves two purposes: (1) as a framework to understand other instances of engineering innovation, and (2) as a way of validating the model.

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SESSION THREE

Visual reasoning in the design process
H.-H. Tang & L.-H. Tsai

Software authors as designers
A. Woodcock

Does sketching off-load visuo-spatial working memory?
Z. Bilda & J.S. Gero

A role for external representations in architectural design
F. Decortis, S. Safin and P. Leclercq

JS Gero and N Bonnardel (eds), *Studying Designers'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 119-127

VISUAL REASONING IN THE DESIGN PROCESS

The differences between expert and novice

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Abstract: In design studies, information-processing and reflection-in-action paradigms were mainstreams in describing designing. This study however took the viewpoint of the visual design reasoning theory where abstract, conceptual knowledge and perceptually-based knowledge were interlinked. The major purpose was examining the design process using visual design reasoning to discover the essential features of design activities. The minor purpose was to demonstrate the differences between a novice and an expert result from the dissimilar abilities of visual reasoning. Retrospective protocol analysis and DCOCS were utilized to explore the interactions between physical drawing and goal-setting. Two main findings were: visual reasoning occupied significant portion of the design process, and to continuously apply visual reasoning is the essential ability of an experienced designer. The idea of visual reasoning was discussed.

1. Introduction

Sketches made by designers during the design process play multiple roles for both designers and the design process (Purcell and Gero, 1998). They serve as an external memory to augment the limitation of human cognitive abilities, as the medium used to communicate with themselves and others, and as the triggers enabling designers to reason a design problem (Suwa, Gero, Purcell, 2000; Goldschmidt, 1994, 1991; Schön and Wiggins, 1992).

It is the last role that reflects an increasing recognition that a perception-based view of design sketches is not sufficient to describe their roles in design. This type of conceptual thinking process relates directly to sketches and visual perceptions according to our better understanding of the roles of sketches, and their relationship to different parts of the design process.

The essential relationship between sketches and the design process was highlighted by Schön and Wiggins (1992). The kinds of seeing and their functions in design and the relationship between seeing and the appreciative system were related to the functional references attached to the sketches themselves. The dialectics between figural reinterpretation and non-figural functional references in design sketches was proposed to describe the same idea (Goldschmidt, 1991).

1.1. VISUAL REASONING

An explicit definition of visual reasoning is still emerging, although the concept of visual reasoning in design has been explored in a serial of conference, entitled visual and spatial reasoning in design. In these conferences, some definitions were proposed.

Visual reasoning is the cognitive process that links abstract, concept knowledge and perception-based knowledge (Tversky, 1999). It refers to the drawing of inferences from visual representations to abstract knowledge. Consequently, sketches are different from images such that sketches physically reflect conceptualizations of the visual reasoning process. Drawings are representations of reality and can provide insights into conceptualizations. The representation, segmentation, and orders of depictions reveal the organization and components of the underlying conceptual elements.

Design visual reasoning is the reasoning phenomenon between figures and concepts until the interactions provide satisfactory design requirements (Goldschmidt, 2001). Through the study of regrouping of depictions, Suwa (2001) regarded visual reasoning a mechanism that provide new meaning to regrouped depictions. There depictions and vague concepts enable designers have multiple representations of sketches to reason the design.

These ideas constitute our hypothesis that the conceptual design process using sketches is a visual reasoning where sketches are the media amongst physical, perceptual and conceptual activities, enabling the design process to progress. Sketches provide a mechanism for the logical and systematic thinking process of design to happen, and the mechanism is named design reasoning. During the design reasoning process, a wide range of visual activities are usually involved, including imagery, sketching, perception, associating depictions to meanings. Therefore, the idea of visual reasoning indicates an interaction between external sketches and internal concepts and the complex interactions in-betweens.

The design process is therefore a conversational and iterative process between a designer's internal ideas and external sketches. Inspired by these ideas, this paper addresses the questions: how much visual reasoning occurs in a design process, and whether the ability to visually reason is the difference between an expert and a novice.

2. METHOD

This study applied a retrospective protocol analysis (Ericsson and Simon, 1993). Three experts and seven novice industrial designers participated in a reading-lamp design project. Two war-up exercises were given to accustom subjects to the experimental process. After design sessions, they gave protocols with the aid of videotapes documenting their design processes. The protocol data was segmented and analyzed using the design content-oriented coding scheme (DCOCS) devised by Suwa and his colleagues (Suwa, Purcell and Gero, 1998; Suwa M, Tversky, 1997). The dependencies and inter-linkages among different levels were identified, for example, a designer's perceiving spatial features was described by DCOCS as a perceptual/seeing instance depending on a physical/drawing instance. This kind of dependencies established the linkages between different cognitive levels within a meaningful duration, segment.

Segment was the unit to parse raw protocol that was transcribed from the audio part of the experiment. The segment of protocol was decided along lines of designers' intentions and actions, instead of time unit, verbalization events or syntactic markers. The designer's intention therefore was interpreted in each segment, and each segment represented one single intention of the designer.

The foci of our exploration were the linkages during each segment. They revealed the relationships between designers' cognition and sketches. Two independent coders participated in the encoding process. Details of the encoded process have been published previously (Tang, 2002).

Finally, two distinct subjects were selected to further analyze according to the following criteria: 1. both design and experimental processes were smooth. 2. Both design sketches were rich and concepts were good. 3. Their experiences in design were distinctly different. One was very good award-winning master student, and the other was an excellent award-winning design practitioner with 16 years of experience in industrial design.

3. How to identify visual reasoning

The following is a translation of the transcripts of the expert from segment46 to segment50.

SegmentTimestampRetrospective protocol4618:13I would like to see it from details and see if there is anyplace I can improve 4718:23At this time, I found that ..that wheels are too ugly4818:30So I hope to give it a …without wheels….a base like a Frisbee 4918:35This is to provide better feeling of that you can walk around5018:43That this time I am thinking the structure from side view….later to see if I can play with the form from 3 dimensions. In the video, the subject looked at the upper circle area and drew the shape in the bottom circle, Figure 1.

TABLE 1. Segment 46-50 of the retrospective protocol of the expert (MID 92 E01)

Segment	Timestamp	Retrospective protocol
46	18:13	I would like to see it from details and see if there is anyplace I can improve
47	18:23	At this time, I found that ..that wheels are too ugly
48	18:30	So I hope to give it a …without wheels…a base like a Frisbee
49	18:35	This is to provide better feelling of that you can walk around
50	18:43	That this time I am thinking the structure from side view…later to see if I can play with the form from 3 dimensions.

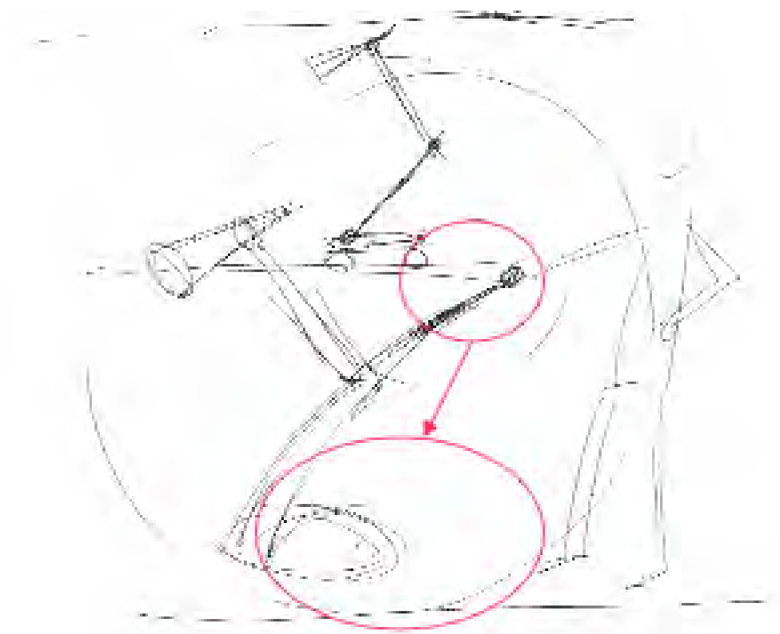

Figure 1. The drawing activities during segment 46~50

Based on the retrospective protocol and corresponding activities, we speculated that the subject was trying to reason the direction for improvement through reading his existing depictions. With the segment number and the encoding of goal-setting, we described his design process as follows. He tried to modify the original shape (segment 46, UG), realized the wheels were ugly (segment 47, AG), regarded them inappropriate to the design goals and modified the shape to a Frisbee (segment 48, AG), and finally the Frisbee shape fitted the function of moving around, the design goals (segment 49, AG). After this serial of reasoning, he started another goal by reading the shape from different angel (segment 50, UG). Here UG stands for an unsatisfied goal-setting and AG for an achieved goal-setting. According to DCOCS, the design process of segment 46~50 could be further represented as Table 2.

TABLE 2. The encoded table of segment 46~50

Segment No.		46	47	48	49	50
Physical	D/L-action	L	D/L	D/L	L	Dc/L
Perceptual	P-action			Psg		Pfp
Functional	F-action		Fn	Fn	Fo	
Conceptual	Goal	UG	AG	AG	AG	UG

There were three visual reasoning segment identified, segment 46, 47, 48. In segment 46, a goal-setting triggered looking actions, and this looking action resulted in an evaluation in the following segment. Therefore, a top-down process with reading sketches resulted in a progress of design process, an evaluation of current design. This reasoning process continued until the goal was satisfied. What we can find is a systematic way of using sketches to setup a new sub-goal that can then trigger a reasoning process through the media of sketches. During this reasoning process, sketches, seeing, perceiving were close connected, and thus a visual reasoning process through 3 segments was identified. Segment 49 and 50 were not regarded as visual reasoning segment because they did not trigger the next segment.

With the definition of visual reasoning segment, we can than examine the portion of visual reasoning in a design segment and the difference between the expert and the novice.

4. The differences between expert and novice

The expert produced 8 concepts and 22 sketches of vertical development, including details and modifications of the 8 original concepts. In the developing of the first 3 concepts, the expert occasionally paused and gave up, and in the following concepts, the design process was stable and the previous 3 concepts were further developed. In the concept name, 2-1 indicated the concept was related to concept 1, but stood as a complete concept. Table 3 presented the encoded results of the expert.

TABLE 3. The encoded results of the expert

Concept Name	Segment Number	V.R. Number	V.R. Ratio (V.R./ segment)
1	37	11	30%
2	28	15	54%
3	9	4	44%
4	40	20	50%
5	44	25	57%
6	66	31	47%
2-1	30	19	63%
3-1	37	23	62%
Sum	291	148	51%

The novice produced 9 concepts and 12 sketches of vertical development. The content of his design process emphasized much on the modification of the forms. Different concepts were not connected. Concept 9 was his favourite idea. Table 4 presented the encoded results of the expert.

TABLE 4. The encoded results of the novice.

Concept Name	Segment Number	V.R. Number	V.R. Ratio (V.R./ segment)
1	16	3	19%
2	25	3	12%
3	39	11	28%
4	31	12	39%
5	17	9	53%
1-1	16	8	50%
7	37	17	46%
8	14	7	50%
9	22	12	55%
Sum	217	84	39%

First, visual reasoning segments occupy more than 40% of the total segments in both subjects. Visual reasoning process is very important in the design process. Second, the expert had 80 percent more of the visual reasoning segments than the novice, and 35 percent more of the segment number in total. Experienced designers have more intensive thinking and more importantly higher rate of applying visual reasoning in the design process. Third, both the favorite concepts of subjects had the highest V.R. ratio, that is the number of the visual reasoning segments in a concept divided by the total segment number. Therefore, better visual reasoning produced a better concept or vise versa.

We plot the differences of visual reasoning in every 5 minutes. In average, the designers had double visual reasoning segments than the novice, and the difference is statistically significant (p<0.05), Figure 2.

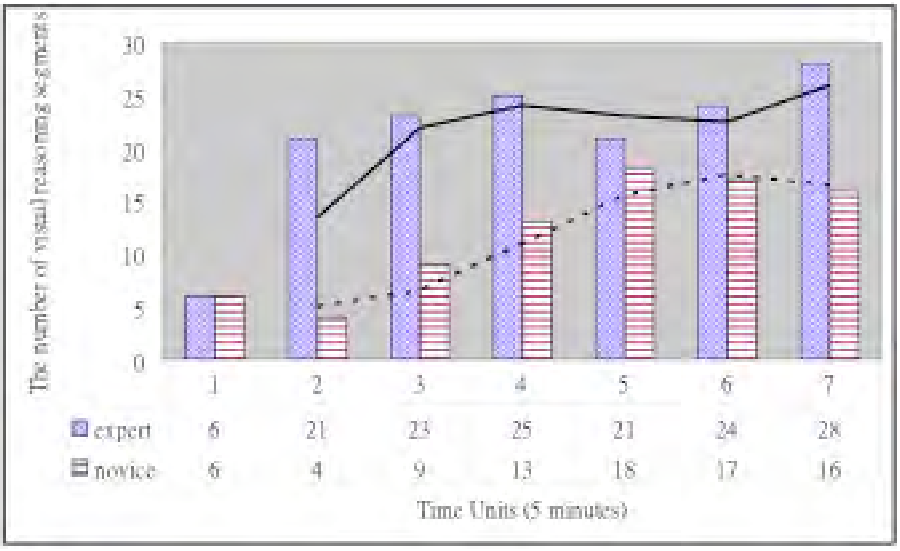

Figure 2. The difference of visual reasoning in every 5 minutes

The visual reasoning plays an important role in the design process. Expert designers can utilize visual reasoning more than the novice.

5. The Distribution of perceptial and conceptual instances

The instance in DCOCS referred to an observed occurrence of a specific cognitive activity; depicting a line was anl instance in the physical cognitive level. It was named physical instances. There were many different kinds of instances in DCOCS corresponding to cognition, but, for the purpose of this study, mainly studied were the instance and its associations with perception and conceptual level. Respectively, they were named perceptual and conceptual instances.

The distribution of the perceptual instances of the novice and the expert showed a significant difference (P<0.05), Table 5. In total, the expert had 70% more of perceptual instances than the novice did.

TABLE 5. The distribution of perceptual instances per time unit.

Time Unit	1	2	3	4	5	6	7	Averaged
Expert	4	26	34	34	20	26	32	25.1
Novice	13	12	16	10	17	16	15	14.1

However, the distribution of the conceptual instances did not demonstrate a significant difference, Table 6. The results further enhanced our assumption about the importance of visual reasoning because the main difference of our expert and novice was not the number of conceptual thinking but the number of perception. The high frequency of perceptual was related to the high frequency of visual reasoning of the expert.

TABLE 6. The distribution of conceptual instances per time unit.

Time Unit	1	2	3	4	5	6	7	Averaged
Expert	13	41	37	20	14	34	42	28.7
Novice	19	17	26	40	23	15	18	22.6

In conclusion, visual reasoning occupied significant portion of the design process as well as perception. Seeing related activities are crucial in the design process. Second, to continuously apply visual reasoning is the essential ability of an experienced designer. An experienced designer sees more often and applied its consequence better.

Quantatatively, we can find some evidence about the visual reasoning, but qualitatively there are still many issues remained to explore. Our next step is to plot the interrelationship between design intention, visual reasoning, perception and conceptual instances. More detailed operation of visual reasoning hopefully could be found.

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SOFWARE AUTHORS AS DESIGNERS

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Abstract. A pilot study was conducted to investigate the extent to which software authorship[1] demonstrated characteristics normally associated with reflective practice. To determine this, verbal protocols were collected from software authors undertaking a 'real task'. Results suggested that programming could be regarded as a design activity, that different forms of reflection did take place, and that the collection of reflections and moments of surprise may lead to a greater understanding of both design and software authorship.

1. Introduction

Programming has not been widely studied by design researchers. Through a long association with software authors, who design and implement their own programmes as recreational activities rather than work, I became interested in the similarities between software authorship (SA) and professional design practice, in terms of the creative act, planning and implementation and more particularly movement through the design solution space. I believed that looking at programming as a design activity could lead to new insights into professional practice that could have ramifications for both software authorship and design research.

A preliminary perusal of the computing literature revealed few studies apart from Winograd (1996) and Schön (1996) that had considered programming in this manner. When programming was talked of as an art or craft, such discussions were invariably linked to a discussion of programming activity, either planning or implementation, rather than on the behaviour exhibited by the programmer – such as problem solving, creativity and professional competencies. I have deliberately distanced myself from

[1] Software design, software authorship and to some extent programming are used interchangeably. The focus of interest is on the practitioner who writes and tests the code such as the developer of shareware.

current debates in software, previous research regarding nomenclature, novice vs. skilled programmers, cognitive psychology etc.

Undoubtedly the precedents for this research have been set by Schön's seminal works on reflective practice (1983 and 1987), later in Winograd (1996), and Ericcson and Simon's (1993) use of protocol analysis, and their application by Dorst (1997) in the study of design activity.

From my own art and design community, there is little interest in software design per se, unless it is part of creative production. Opportunities for cross over between the two disciplines might exist, for example, on the one hand in terms of recognition of software design or authorship as a design profession, on the other, for example, by providing further insights in to the way in which reflection mediates action in a different context.

The focus of this research is on how software authors, working on their own, move around the design solution space as they undertake a realistic, complete design task. The research aimed to address four questions:

1. Can software authorship (SA) be regarded as a type of design activity?
2. Can design research methods, employed in the study of design activities in other domains be used to gain new insights into the process?
3. Do software authors exhibit periods of 'reflection' and if so, what are these about, and what is the value of these in terms of their current activity?
4. Would studying SA in this way be of any practical value?

The paper presents evidence in support of each of these elements.

1.1. CAN SA BE REGARDED AS A DESIGN ACTIVITY?

Table 1 indicates some of the similarities shared by the two disciplines

More recently the trend in industrial design has been towards looking at the creative, social and psychological aspects of designing (Cross, 1995) and looking at design as reflective practice, i.e. focusing on professional practice rather than theory. This pilot study makes the first steps in applying a similar approach to software design.

TABLE 1. Overview of similarities between design and SA

Factor	
Requirement	Mostly generated externally
Design brief	Can be problematic in terms of degree of specificity
Artifact	Can take many forms; developed in relation to a perceived need
Role of designer	To apply existing skill, knowledge and experience to the task in hand
Final artifact	Will more or less meet the initial requirements but will be a compromise
Designer	Not usually the client
Good design	Should delight, be fit for purpose and functional; or exhibit firmness, commodity and delight
Design compromise	Shaped by external factors such as time, ergonomics, finance, technical issues, marketing and windows of opportunity
Professional status	Relatively young professions, adopting methods from other domains eg psychology, mechanical engineering
Process	Evolves very quickly; may be team or individual effort, ‘chipping’ away to reach the final design; rush to start
Evolution of process	From waterfall, to cyclical to concurrent design and rapid prototyping
Media	The final artifact may not reveal the process of its creation – a car starts off as a drawing, a game as lines of code
Production	Development of durables. Mass produced products for people, based on the integration of the interests of users, industry, society and the environment),” Buijs (1997)

1.2. CAN DESIGN RESEARCH METHODS BE USED TO INVESTIGATE SA?

The many parallels to be drawn between the two disciplines make SA an appealing area of investigation for design research. Both software and industrial design evolve very quickly – whereas the industrial or product designer may generate hundreds of rapid sketches, the software author will often generate, and later discard, hundreds of lines of code – when searching for the optimum solution to one or more problems. Each solution will have ramifications for the final solution, and impact on different sub areas.

Software designers spend a lot of time validating and refining their designs (debugging). “Testing is not just concerned with getting the current design correct. It is part of the process of refining the design….Even the smallest bit of code is likely to be revised or completely rewritten during testing and debugging. We accept this sort of refinement during a creative process like design," Reeves (1992). Likewise a designer, may draw, rubout and redraw a line on a concept sketch of a car time and time again, until the curve is perfect. Both activities indicate that the designer is entering into a conversation with the design.

Trapping the verbalizations of software designers engaged in such activities may lead to a new understanding of their professional practice in a similar way to studies undertaken of product designers. Additionally, the difference in media (written code, as opposed to hand drawn sketches) may make it easier to understand the underlying processes. In answer to the first two questions, there are sufficient parallels between software authoring and design in general for it to be amenable to study as a design activity.

2. The investigation

Given that SA may be regarded as a form of design, there are many possible avenues of investigation, for example the role of the specification, emergent requirements, movement from brief, through concept to detail design. In this preliminary study I was initially interested in the way in which movement occurred through the design activity, for example evidence of explicit goal oriented working, concurrency and whether designer's verbalizations were similar to those engaged in other design activities and whether I could find periods of reflection.

If software authors are reflective practitioners, engaged in a conversation with the design problem, then periods of reflection should be noticeable – but what will they look like?

For Schön, all professions are design like in so far as "they all consist in conceptualising, planning, patterning or otherwise establishing cognitive order", Walks (2001) p43. During the course of design, problems may be experienced, either as a consequence of previous actions or because of a lack of understanding of the requirements of the solution. At such times "practitioners apply tacit knowledge-in-action, and when their methods do not work out, they do not take time out, to reflect or disengage, but reflect in action using the knowledge of their practice rather than the knowledge of science." Walks (op cit), p 44. Design studios are places where such experience and reflection can be acquired and shared. If such similarities could be found, this may lead to a reappraisal of software authorship as professional practice, perhaps with the development of computer studios as opposed to computer laboratories.

Protocols of design sessions can be studied to show movement through the design process in terms of the setting and meeting of goals and subgoals. Although I am interested in tracing this movement, which can be seen in the transcripts gathered during this work, for this paper I would like to focus primarily on identifying periods of reflection. What I would hope to do in subsequent work is to identify the relationship between reflections and the setting of goals and subgoals, to mediate movement through the solution space (Gill,1987).

When a designer makes a move (ie towards generating a solution), that move will produce a series of results, not just the ones that were specified or hoped for. For programmers, a piece of code may or may not work in the way it was intended (ie meet its subgoal) but it may have an effect on other aspects of the program (for example by changing the instantiation of variables). Looking at what has happened in debugging and testing may lead the designer to realize that they had made both simple coding errors, but also might not have fully understood the requirements of the solution to begin with. So, during debugging the programmer may enter into a conversation with the design problem. This in turn will lead to future actions. “This unpredictability is a central attribute of design-it is not necessarily the defining one, but it is important. It means that there is no direct path between the designer's intention and the outcome” Schön (in Winograd, 1996). By entering into a conversation with design, the complexity becomes clearer. A study of the software design process, especially debugging may reveal that “sometimes, the designer's judgments have the intimacy of a conversational relationship, where (s)he is getting some response back from the medium, (s)he is seeing what is happening-what it is that (s)he has created-and (s)he is making judgments about it at that level” Schön op cit). This understanding then serves as a “springboard to a new round of problem-solving inventions” or to put it another way, “as you work a problem, you are continually in the process of developing a path into it, forming new appreciations and understandings as you make new moves.” (Schön, 1976)

Although this may strike resonance with software design practitioners, it is important to determine whether such occurrences can be found under ‘experimental’ conditions, how these can be captured, whether there is any variation in their manifestation, the extent to which these bear similarities to other domains, or may provide new insights into the study of reflective practice.

Three types of reflection are recognized:

Reflection-in-action. This is associated to the experience of surprise. Sometimes, we think about what we are doing in the midst of performing an act. When performance leads to surprise-pleasant or unpleasant-the designer may respond by reflection in action: by thinking about what you are doing while doing it, in such a way as to influence further doing. The designer is reflecting in action, both on the phenomena that is being represented (through his drawing) and on his previous way of thinking about the design problem. Schön described this as ‘backtalk’. Where you discover something totally unexpected-"Wow, what was that?" or "I don't understand this," or

"This is different from what I thought it would be-but how interesting!" Backtalk can happen when the designer is interacting with the design medium. In this kind of conversation, judgments are made such as, "This is clunky; that is not," or "That does not look right to me," or just "This doesn't work." The designer's response may be "This is really puzzling," or "This outcome isn't what I expected-maybe there is something interesting going on here."

Stop and think. Here, the designer exhibits a **reflection-on-action**, pausing to think back over the activities in the project, and exploring the understanding that has been brought to bear on the task. This may include a new theory of the case, reframing the problematic design situation in such a way as to redefine, interactively, both means and ends.

Reflection on practice, the designer may surface and may criticize tacit understandings that have grown up around repetitive experiences of designing.

A design session may yield instances of all three types of reflection. The pilot study described below was designed to determine whether any of these types of reflection could be found, and the extent to which potential instances could be classified into those categories. Although previous studies have been mainly conducted on design dyads, this study was conducted on SAs working on their own.

2.1. THE TASK

'Sheepdog' is a real time, though fairly obscure game that can trace its ancestry to the early days of home computers when the blocky nature of the graphics available did not detract too much from the enjoyment of the game. The fact that blocky graphics are acceptable make this game suitable for a design experiment, in which I was interested in looking at game design and authoring rather than graphic design. Additionally it was selected because it was likely to be unfamiliar to the participant and the creation of a rudimentary game was achievable within a 3 hour time frame.

The principle of the game is that several "sheep" need to be herded into the "sheep pen" by the "sheepdog". The sheep move around on their own, but are influenced by the behaviour of the sheepdog, which is controlled by the player (either through mouse or keyboard controls). There are different targets that can be set - e.g. time limits, no sheep to escape from the field, a point score ... and so forth. A representation of a basic screen is shown in Figure 1.

Critical to the design is the way the sheep are programmed to move both in relation to their environment, and according to their intrinsic properties. At the most sophisticated level, this could include 'environmental' factors such as the field edge, the pen, other sheep (position and velocity), the dog (position and velocity). The authors were encouraged to avoid programming peripheral elements such as option menus, high score tables etc, and concentrate on the basic mechanics of the game.

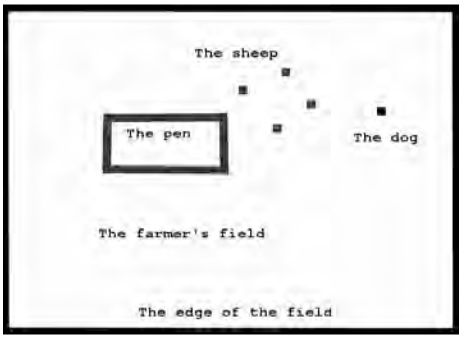

Figure 1. Representation of the game elements for Sheepdog

2.2. METHOD AND PARTICIPANTS

Participants were required to be proficient in a third generation computer language, ideally with an interest in games programming. All were recruited locally, interviewed about their level of competence, assessed for their ability to talk out loud and told the purpose of the study and nature of the trial. Five participants took part, generating over 20 hours of material.

Sessions took place in the Usability Laboratory at the Design Institute, Coventry University, which allowed sessions to be videoed and participants unobtrusively observed. The researcher intervened to provide refreshments, talk to participants and remind them to keep verbalizing.

Prior to the session necessary applications were uploaded on to the in-house computer so that the participant would use a version of the software they were familiar with and provided with a written design brief. They were asked to start thinking about the task and develop the game whilst providing a verbal stream of consciousness. A period of three hours was allocated. Although this would not give sufficient time to programme advanced features, it was considered long enough for the mechanics of a basic game to be developed. All participants managed to complete and test the basic functionality of the game in this time.

2.3 ANALYSIS

The video capture allowed recording of the screen, the face of the participant and verbalizations. The data is currently still being analysed.

11 categories were used to explain 'broad' activities (eg reading brief, writing on paper, looking at graphics screen)- Table 2, column 4.

Programming activities were further categorized in terms of programming (ie new code), debugging, verification etc. These will be subject to later analysis to determine whether there is an association between, for example, periods of reflection and programming activities. It seems that there is a relation between looking at the graphics screen (which provides visual feedback), reflection and eureka moments.

The transcript was chunked into meaningful segments on the basis of the initial classification of topics being addressed (last column, Table 2). The categories used emerged from the data, but were fairly consistent across the participants regardless of programming language used.

TABLE 2. Example of initial classification

Chunk	Transcript	Time	Activity	Initial classification
6	Uh, can't type	2.30	Programming	Comment
7	If I place the sheep randomly	2.50	Writing	Sheep position
8	Ahah. To make the sheep move….um	3.40	No action	Sheep movement
9	If I can place them randomly, then move them more or less in a group	4.00	No action	Position and movement
	But static movement would be boring		Programming	Sheep movement
	That's going to be a difficult one	4.30	Programming	Comment

Further coding, using an adaptation of the scheme developed by Dorst (1997), was used to consider the flow of the design in terms of problem identification, solution and verification, with the expectation that this can be mapped on to periods of naming, faming and moving in the next stage of the analysis. For this study, phrases which were classified initially as 'comment' were selected for further study with a view to determining whether they could be classified as Eureka moments, or times of 'reflection–in' and 'on-action' and 'reflection-on-practice'.

3. Preliminary results

In looking at reflections my interest was specifically in:

- The contributions reflections made to the movement through the solution space
- Whether the reflections showed that the problem was talking to back to the software author.

- Comparing the type of comments generated by the SAs with those generated by designers in other domains

My interest in these issues is in understanding, and finding ways in which we can learn about the very short instances where an insight into a problem/or a surprising solution leads to a shift in an understanding – as exemplified by the spirals in Figure 2. If these instances could be found in the transcripts and were associated with any particular activity (eg debugging) or type of task (such as calculus) then tools could be developed to support SAs.

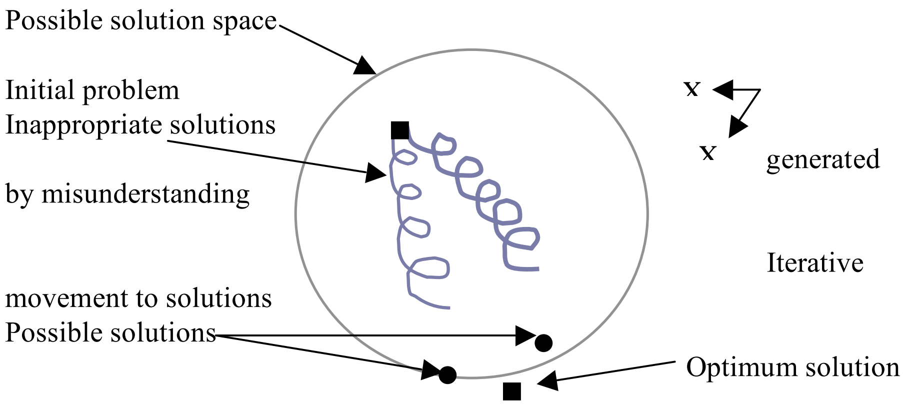

Figure 2. Movement through the design solution space (Gill, 1987)

3.1 REFLECTIONS

All participants reflected-on-action. These occurred throughout the session and were mainly integral to the activity, ie they did not occur when the participant stepped out of the activity. One participant did not reflect as much, but this might have been due to the experimental setting – some participants find it easier to produce a verbal stream of consciousness than others. The reflections were classified as relating to

- Their own ability, eg mathematical reasoning, programming and memory such as:
  "*hmm, I kept the wrong thing….I do that a lot, I'm very forgetful…you can find that takes so long*" subject 3 while changing his code
- Elements of the specific task eg game play
- Programming in relation to the task eg errors and coding strategy
  "*classic copy and paste mistake.*" Subject 3 while copying code for 'sheep behaviour' to the 'dog' and again

"*there's probably nothing as much , that causes so many bugs as cut and paste*"

Given the nature of the investigation it was not anticipated that there would be many instances of reflection-on-practice that may lead to changes in professional practice. This belief was confirmed. Where such reflections occurred these seemed to be a result of the experimental setting – more as an aside to the experimenter. For example, Subject 1 in his last session made the following reflections regarding his practice. These were occurring outside of the main activity and were perhaps made solely for the edification of the researcher.

TABLE 3. Reflections by Subject 1

TIME	**Transcript**
1.15	*"again, y'know I…something at the beginning of the whole project told me what the data structure should do, my general knowledge of this type of environment if you like, the sort of data structure would be useful and they've….I've been able to get the up and running and they…..I think they've been sort of*
1.30	*been useful in establishing um, where the problems are, the different ideas have given me a feel for the lie of the land…that acts as a sort of like an impetus for me then to go forward into pen and paper stage*
1.45	*Strangely enough I don't think it would have been worthwhile for me to have gone into pen and paper stage first because you are committing yourself to ideas there which might fall apart, um very early on in the process*

Throughout the sessions the SAs could be heard drawing on their experience from other projects to assist in the design (for example, the use of libraries of sub routines, programming a clock to control the animation rate, structuring of the code), and being mindful of their own weaknesses when pinpointing errors (for example, in the use of cut and paste). Most errors were associated with:

- production errors (eg syntax, spelling, cut and paste problems),
- coding imprecision
- not understanding the requirements of the solution.

Reflections-in-action were the ones most closely associated with changes in movement through the design solution space.

This is illustrated in the engagement with task, as exemplified by Participant 2 (see Table 4 below). This transcript is taken from early in the session, once the basic elements of the game had been formalized (see Figure 1). In this set of verbalizations the participant is starting to consider the way in which the movement of the dog will influence the movement of the sheep. The time frame for this was just over 2.30 minutes, during which the participant swapped his attention between three screens (programming, debugger and graphics screen) in order to ascertain why the coding was not producing the effect he required. Some participants generated code they knew was not quite right to begin with – to get something up that they could work with – although, in this case the participant thought he had found a solution until he tested it on the graphics screen (7.20).

The verbalizations clearly demonstrate his problem solving strategy – which commences with starting to sort out syntactic problems (missing words at 7.30, signs the wrong way at 8.00). Once these have been solved, and the code still does not produce the desired effect, he starts to look more deeply into the requirements of the solution culminating in the development of a more sophisticated solution. During the course of this journey he also discovers another problem, the fact that once the sheep or the dog reach the corner of the screen they can't move out. This problem is 'parked' and returned to later. Many instances of the behaviour were found in all sessions.

If the time frame is considered and the data subject to a detailed analysis, the actual picture that emerges is very complex. This was one of the reasons for selecting to study single designers rather than design dyads. Here the SA is immersed in the task and is in control. He does not have to worry about co-ordinating and integrating his actions with a peer or an expert, or become distracted by entering into social discourse or role maintainence. Table 4 has been simplified for the purposes of exemplification, in the more detailed activity analysis there are rapid switches of attention between screens, with screens being cross checked very few seconds.

Table 4 also exemplifies that reflections are integral to the activity and that they can be of very short duration. We require postgraduate students to reflect on their work and the surprises they encounter in their design journals. Here the focus is at a more micro-level, showing the way in which reflections may cause small shifts or changes of direction along the course of an activity, rather than the more profound reflections documented in design journals.

TABLE 4. Overview of engagement with a problem by Subject 2

Time	Transcript	Topic	Action	Reflections, surprise, backtalk
7.20	<laughs>		Comment	Surprise
7.30	as it gets near the sheep it either vanishes or jumps into the nearest corner which isn't ideal	Sheep movement	Watching graphics screen	Reflection
	Oh I forgot to put that		Debugging	

	in			
	One word and it does completely the wrong thing			Reflection
	Christ… that doesn't…oh that's		Watching graphics screen	Backtalk
8.00	Oh…okay		Programming	Backtalk
	I was doing greater than			
	So if the dog was greater than 50 pixels, I'd say move whereas what I wanted to say was closer than 50 pixels	Dog /sheep interaction		
8.20	And it doesn't seem to work		Watching graphics screen	Surprise
	50 pixels is probably a bit big		Programming	Reflection
8.30	Let's change it to 20			
8.40	Well its still very big			
	Can't actually move anywhere that doesn't make the sheep run away from me		Watching graphics screen	Backtalk
8.50	And if you're in the corner you're stuck			
	Uh			
	Let's just make it something like 10 even		Programming	
	'cos 10s as big as the er actual dog isn't it			
9.20	Why is it doing that?		Watching graphics screen	Surprise
	Unless I've forgotten to put an 'and' in somewhere		Looking at code	Backtalk
9.30	Oh so what I need to do is combine these two			
9.40	Oh that's really stupid		Watching graphics screen	
9.50	Oh that's annoying			
	What its doing is changing its mind independently			

10.15	So it doesn't care if you are not near….. it depends if you are in line with the sheep			
	So I've got to change that			Reflection
10.40	I have a feeling this is going to get confusing			
11.00	This is where bugs come in to programs			
	So what I'm doing now is making it a bit more exclusive and saying don't do this unless its near on the 'x' and 'y'		Programming	

3.2 BACKTALK

Although undoubtedly the analysis in terms of reflections, surprise and backtalk needs further refinement, it is very clear from Table 4, that the SA is engaged in a conversation with his design. This was common across all participants. Also, the SA is actively engaged in triangulating, or integrating the information he is receiving from the different screens in order to find out where the proposed solution is not working. This may be characterized as writing the code, verifying it, looking at the instantiation of the design on the graphics screen, debugging it, and then moving back to the design or checking stages. One of the benefits of working with SAs is that it seems comparatively easy to chart this conversation with coding activity (rather than drawing) and the verbalizations seem to be quite natural.

3.3 SURPRISES

One of the most satisfying parts of the research was finding that the phrases used by the SAs to express their surprises were almost identical to the ones detailed in the literature. These included comments such as "wow", "oh no", "why's it doing that", "I didn't expect that…….", "that means that," and laughter. These occurred mainly during debugging or visualization of the code (in the graphics screen), and occasionally when pen and paper was used to work out mathematics problems.

3.4 PARALLELS WITH DESIGN ACTIVITY

Although not the primary focus of attention in this paper, the reflections also revealed evident parallels to other design domains. For example, in using a basic approximation to a solution as a starting point. For designers this may be a very basic sketch, for programmers it is rudimentary code as evidenced below.

> "*okay…here, I'm going to get something, anything at all working as fast as possible. That way I get a good feeling, and , er, instant gratification*," subject 3.

In the necessary toleration of solutions that are not correct, but that allow progress to be made on other subgoals

> "*this is going to flicker a lot and I also know how to fix it, but I'm not going to bother for now, although its probably going to get irritating very quickly*," subject 3.

4 Discussion and Conclusions

This preliminary research has shown that it is possible to use design research methods to study programming activity and that periods of reflection can be found that are of a similar nature to those found in other design domains. Not only do the reflections help to solve the immediate problem, they also mediate movement through the solution space. The last aim of the research was to assess whether this approach was of any practical value to the software and design communities.

For the software community:

- Recording verbalizations of expert programmers may reveal shortcomings in both skills and support :
    - Skills. Clearly this is domain specific. SAs may not be aware of their own lack of skills in certain areas, ie they may struggle with the same class of problem in all their work, yet not appreciate that they need training in it. In this investigation all designers had problems with advanced mathematics and visualization of 'x' and 'y' coordinates and were confused about of '+' and '-', '<'and '>' in the context of their programmes. This was evidenced by sometime lengthy problem solving on pen and paper, and relying on running their programmes to understand where the errors were and when the code was not doing what was expected. The follow up interviews confirmed a need for CPD
    - Development of programming support tools. Reframing of the problem occurred most often when the code did not work as expected after all the production errors (eg typo's) had been identified. More complex errors required the whole problem to be reconceptualised. Tools could be developed which aided this.

- Education. Very few references to programming as a craft or profession were found in the literature. Given the crisis in computer education, with fewer people willing to study computer science, it may be time to reappraise the approach to training, and consider programming as a form of design. This would have implications for the type of people recruited into the profession, the type of solutions generated and the manner in which computing is taught. For example, computing is taught in laboratories, design in studios. Yet the most innovative breakthroughs have come from companies that take a more relaxed approach to workspace design and build up communities of practice. There may be opportunities for future research to look at the benefits of reflective practice and computer studios (as in design studios) where talk back is used more extensively to help the programmer understand the complexity of the situation. If such work is undertaken this may have major ramifications for the training of programmers.

For the design research community:

- This pilot investigation has demonstrated that SAs may be studied using methods developed in design research. For me, at least it analysis of a text based media has some benefits in terms of ease of interpretation over looking at design drawings. The transcripts clearly show that a conversation is being entered into, and the graphics screen and debugging provide a voice for the author to listen to.
- Scale of the reflections. When studying reflection and surprises, it is easy to be lured into a study of just the major breakthroughs and profound insight. In this study the reflections that steered the design may only have lasted several seconds. Yet it is these almost casual instances that are crucial to shaping the design.
- Traditionally reflective practice has been studied through looking at expert and novice, dyadic interactions. This research has shown that designers, in this case software designers, enter a conversation with the design problem, by themselves, and that this can provide meaningful insights into activity.
- Experimental effects. A clear distinction could be found in the transcripts between reflections that were made during the course of the work, and those instances when the SA stepped out of the task and started to make comments that would be pleasing to the researcher. This may also be true for dyadic interactions where the need to interact or impress a partner may result in unnatural behaviour.

5 Reflection

This initial research project had very modest aims and fulfilled these by showing that there were sufficient parallels between design and software authorship to suggest that it could be useful to study SA as a form of design and that the application of design research methods may provide new insights into programming activity. The results presented in this paper have been merely indicative and illustrative of the approach and type of findings that will emerge.

It is too early in the work to consider whether this line of research may bring benefit to any particular area of programming. It was certainly very difficult to find a position for this research within computing, as evidenced by the problems recruiting participants, and generating on-line discussions about the practice of programming.

It might be self evident that software authors are reflective practitioners in much the same way that everyone engages in reflection as part of their everyday lives, but few studies have considered this. However, for me one of the surprises has been that reflections do occur so often, they are small but do affect design progress – that the programme talked back – and given the scope of the project it was possible to capture some of these. Future analysis will look in more depth at the way the reflections mediate movement through the solution space and are related to naming, framing and moving or working towards sub goals.

Acknowledgements

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DOES SKETCHING OFF-LOAD VISUO-SPATIAL WORKING MEMORY?

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Abstract. Empirical studies on visuo-spatial working memory show that the capacity of the visuo-spatial working memory is limited when visuo-spatial tasks are done using imagery. Externalization is needed to off-load the visuo-spatial working memory. For the same reason drawings and diagrams play an important role in designing. This paper presents the cognitive activity differences of three expert architects when they design in blindfolded and sketching conditions. It was observed that all participants' overall cognitive activity in the blindfolded condition dropped below their activity in the sketching condition, approximately after 20 minutes during the timeline of the design sessions. This drop in performance can be explained by higher cognitive demands in blindfolded conditions. We concluded that sketching off-loads the visuo-spatial working memory.

1. Introduction

A previous case study showed that expert architects were able to come up with a satisfactory design solution when they were not allowed to sketch (Bilda and Gero 2005). The study suggested that sketching might not be the only way to conceptually design for expert architects. If designers are able to design blindfolded, then why do they prefer to sketch? The answer may be that sketching makes thinking easier; by "seeing it" and "storing it". In other words sketching puts much less load on the cognitive processes needed to design. Evidence in working memory research supports that the cognitive load should be higher in a blindfolded exercise since image maintenance and synthesis of images requires more executive control resources (Pearson et al. 1999; Vecchi and Cornoldi 1999, Baddeley et al 1998).

2.Background

Imagery has been claimed to be the visuo-spatial sketchpad (VSSP) of the mind in the model of working memory (Baddeley 1986; Logie 1995). It is considered to be an alternative imagery model. In Baddeley's (1986) model the visuo-spatial sketch pad (VSSP) is likely to be related to visual perception and action while central executive is related to attention, control of action and planning. The VSSP is hypothesized to produce internal representations and process visual or spatial material. The role of working memory in design has been emphasized as a workspace for cognitive processes that retains information in visuo-spatial or verbal modes since designing involves the use of both verbally coded and visually coded knowledge. The workspace is hypothesized to provide coordination of visual, spatial and verbal information and retrieval from long term memory with a central executive.

In design research, use of imagery alone during the design activity is not considered to be sufficient since externalization is needed to allow design reasoning. Imagery studies have emphasized the role and necessity of externalizations for mental synthesis of parts/objects as well as for interpretation (Anderson and Helstrup 1993; Vertijnen 1998; Kokotovich and Purcell 2000). These studies provide evidence that maintenance, transformation or inspection of images/shapes would be very difficult unless they are externalized. Research in visuo-spatial working memory claims that maintaining and transforming visuo-spatial information demands central executive resources, in other words requires mental effort (Baddeley 1986; Logie 1995). Based on a large body of empirical evidence found in this literature, imagery activity intensively uses up working memory resources. Externalization is said to free up the working memory by storing/ externalizing the visuo-spatial information so that the other tasks can be carried out effectively. There is also evidence that the capacity of the visuo-spatial sketchpad itself may be limited and that performing any sufficiently complex visuo-spatial tasks would be impossible without the involvement of the executive functioning (Baddeley et al. 1998). Other empirical studies on visuo spatial working memory (VSWM) also show that the capacity of the VSWM is limited when visuo-spatial tasks are done using imagery (Ballard et al. 1995; Walker et al. 1993; Phillips and Christie 1997). Externalization is needed to off-load the visuo-spatial working memory. For this reason drawings and diagrams play an important role in designing. This paper reports on the cognitive activities of architects designing with and without the aid of sketching.

3. Method

The three architects who participated in the study (two female and one male) have each been practicing for more than 10 years. Architects A1 and A2 have been awarded prizes for their designs in Australia; they have been running their own offices and also teaching part-time at the University of

Sydney. Architect A3 is a senior designer in a well-known architectural firm and has been teaching part-time at the University of Technology, Sydney.

The participants first engaged in a design process where they are not allowed to sketch. This phase is called the experiment condition where they receive design brief 01. Design brief 01 requires designing a residential for a painter and a dancer. In the experiment condition we used a similar approach to that taken by Athavankar (1997): we had the designers engage in the design process while wearing a blindfold. After an interval of at least a month after the experiment condition the three architects were engaged in another design process where they were allowed to sketch. This phase is called the control condition where they receive design brief 02. Design brief 02 requires designing a house for a family with 5 children.

3.1. SEGMENTATION OF PROTOCOLS

The audio files of the concurrent verbalizations were transcribed and then segmented. The protocol was segmented using the same approach as for segmenting sketching protocols, i.e. by inspecting the designer's intentions (Suwa and Tversky 1997; Suwa et al. 1998). In the segmentation of sketch protocols, not only verbalizations but also video recordings of the sketching activity support decisions to flag the start and end of a segment. The drawing actions are inspected as cues for finding the changes in intentions. In the blindfolded condition information about the internal design representation state is extracted from the description of the current image or scene the architect talks about. The architect's attention may shift to a different part or aspect of the current image and this becomes the cue for change of intention. Keeping track of the changes in the descriptions of images/scenes supports our decisions to flag the start and end of a segment.

3.2. IMAGERY AND SKETCHING CODING SCHEMES

Recent research on sketching studies proposes that design thinking progresses at physical, perceptual, functional and conceptual levels in parallel (Suwa et al. 1998). Physical actions refer to drawing and looking, perceptual actions refer to interpretation of visual information, functional actions refer to attaching meanings to things, and conceptual actions refer to the planning of the actions and initiating actions for design decisions.

The imagery coding scheme borrows action categories from the sketching coding scheme. It consists of six action categories; visuo-spatial actions (VS), perceptual actions, functional actions, conceptual actions, evaluative actions and recall actions. We selectively borrowed actions from perceptual, functional, and conceptual action categories in the Suwa et al. (1998) coding scheme. The selected codes, Table 1, are the ones found to be highly correlated with drawing actions during the sketching activity of experts (Kavakli and Gero 2001).

TABLE 1 Perceptual, Functional, and Evaluative Actions

Perceptual Actions	
Pfn	Attend to the visual feature (geometry/shape/ size/ material/color/thickness etc) of a design element
Pof	Attend to an old visual feature
Prn	Create, or attend to a new relation
Por	Mention, or revisit a relation
Functional Actions	
Fn	Associate a design image/ boundary/part with a new function
Frei	Reinterpretation of a function
Fnp	Conceiving of a new meaning
Fo	Mention, or revisit a function
Fmt	Attend to metric information about the design boundary/part (numeric)
Evaluative Actions	
Gdf	Make judgments about the outcomes of a function
Gfs	Generate a functional solution / resolve a conflict
Ged	Question/mention emerging design issues/conflicts
Gap	Make judgments about form
Gapa	Make judgments about the aesthetics, mention preferences

Perceptual actions category, Table 1, includes creating or attending to a new/old relationships between things, as well as (new or previously perceived) visual features of the things. Functional actions category refers to designer's actions when s/he attaches a meaning to an entity, or an image. Types of functional actions are listed in Table 1. The evaluative actions category has been formed during our explorations with the blindfolded and sketching design protocols. These actions refer to information at the conceptual level. During the think-aloud, we observed designers' self-talks in terms of idea evaluation or questioning cycles. In this inner dialogue some designers question ideas or emerging design issues (Ged) before evaluating them. They might generate a tentative a functional solution (Gfs) in this inner dialogue. The evaluation of the ideas is classified into three types:

1. evaluation based on a function that is previously introduced, i.e. evaluating by making judgments about the possible outcomes of the function (Gdf),
2. evaluation based on form of the design entity, in other words by making judgments about form (Gap), and
3. evaluation based on aesthetical preferences of the designer (Gapa).

3.3. CODING

In this study imagery processes are hypothesized to be similar to perceptual processes, the basic assumption is that all percepts are internal, where in sketching condition they are dependent on the act of drawing, and in blindfolded condition dependent on the internal representation. Since drawings are externalizations on paper, the perceptual features/ relations can be easily extracted and coded. One can question how we access the content of the internal representation. The imagery protocols demonstrate very detailed descriptions of images and scenes which refer to a dynamic internal representation. These verbalized descriptions make it possible to extract the relationships between design elements as well as the visual features. It is also necessary for the coder to keep track of the verbal descriptions of the imagery content and confirm them with the elements in the sketch produced at the end.

Each segment was time stamped, and coded with the related coding scheme. The complete audio/video protocol for each session was coded twice by the same coder with a one month period between the two coding passes. Then the codes were arbitrated into a final coding. The coding phase included a first run, a second run and finally the arbitration phase where codes are selected and accepted from first or second run in coding.

4. Results

After completing the coding process, we ended up with more than 1,000 cognitive actions for each design session. We summed the total number of cognitive actions in every 5 minute interval for each participant in both the sketch and blindfolded (BF) conditions. We ended up with 26 data points separately for sketch and BF conditions, where each data point indicates the total number of cognitive actions in 5 minute intervals. We tested if these points are statistically different, Table 2. The F-test probability is 0.0015, which means the variance in cognitive activity in 5 minute intervals is significantly different between sketch and BF conditions.

TABLE 2. F-Test for frequency of cognitive activity in 5 minute intervals

	Sketch	BF
Mean	139.6	150.6
Variance	377.6	1302.6
Observations	26	26
F	0.29	
P(F<=f) one-tail	0.0015	
F Critical one-tail	0.51	

4.1. HYPOTHESIS TESTING

If the variance in cognitive activity is significantly different between the two conditions then this may be due to the cognitive load in sketch versus BF conditions. As a next step we tested our hypothesis: sketching off-loads the VSWM. We divided each design session into two periods; the first 20 minutes and the remaining time in the session. The reason for dividing the sessions into two periods is based on the assumption that cognitive load is accumulated over time, therefore the cognitive load might be less in the first 20 minutes and more in the next 20 minutes. Then we looked at differences in normalized cognitive activity rates, whether cognitive activity was increasing or decreasing from period 1 to period 2. If cognitive activity was increasing in either condition, this means the participant is efficiently designing and cognitive load is handled. If the cognitive activity was decreasing in both conditions then we compare the magnitude of the drop of the activity between the sketch versus BF conditions.

We summed the total number of cognitive actions (X) in every 5 minute interval for each session. The mean (μ) and standard deviation (б) of each session are calculated. The normalized frequency (Z) of the total number of cognitive actions for each 5 minute interval was calculated as Z= (μ - X) / б. Table 3 shows first architect's (A1) sum of cognitive actions and the normalized cognitive action frequencies in each 5 minute interval.

TABLE 3 Sum of cognitive actions and normalized frequencies for A1

Architect A1		Sum of cognitive actions		Normalized values	
Time intervals (mins)		SK01	BF01	SK01	BF01
	0 - 5	143	198	-0.5	0.9
	5 - 10	162	209	1.1	1.2
	10 -15	161	201	1.0	0.9
	15 - 20	140	173	-0.7	0.1
	20 - 25	127	174	-1.8	0.2
	25 - 30	158	148	0.8	-0.6
	30 - 35	154	119	0.4	-1.4
	35 - 40	146	127	-0.2	-1.2
Statistics	mean	148.9	168.6		
	Std. dev.	12.12	34.25		

Table 4 shows the sum of normalized cognitive activity data points in the first 20 minutes (Period 1) and in the remaining minutes of the sessions (Period 2). A1's and A2's performance are above the average in the first 20 minutes during sketching (0.9, 0.2) and BF (3.1, 2.9) sessions. Their performance is below the average for the second period of the sketching (-

0.9, -0.2) and BF (-3.1 and -2.9) sessions. A3's sketching performance increases from first to second period (-1.9 to 1.9), while the same participant's BF performance decreases from first to the second period (0.7 to -0.7).

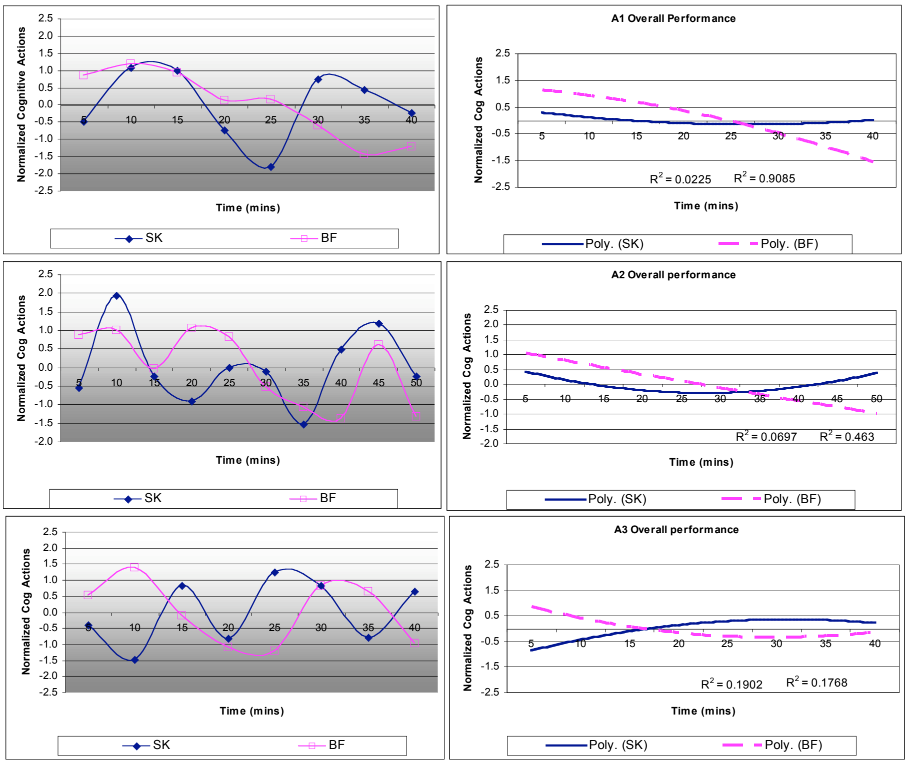
TABLE 4. Overall normalized cognitive activity variances from period one to two

Architect	Period	Sum of normalized activity values		Magnitude of variance between two periods	
		Sketch	BF	Sketch	BF
A1	First 20 mins	0.9	3.1	-2	-6
	Remaining mins	-0.9	-3.1		
A2	First 20 mins	0.2	2.9	0	-6
	Remaining mins	-0.2	-2.9		
A3	First 20 mins	-1.9	0.7	4	-1
	Remaining mins	1.9	-0.7		

The last two columns of Table 4 show the magnitude of the variance in normalized activity values between the first period (first 20 minutes) and the second period (remaining minutes) of the sessions. Note that the magnitude has a minus sign if the activity is decreasing and a plus sign if the activity is increasing from first period to the second. The magnitude of variance in activity is significantly larger in BF conditions compared to sketch conditions, for the three participants' sessions. For A1 the drop in BF condition is 3 times larger than sketch condition (-2 and -6), and for A2 there is no significant change for the overall sketching performance while there is a drop in the BF condition (0 and -6). For A3 the variance value is positive, which indicates an increase in sketching performance, while there is a drop in the BF condition. The variances in cognitive activity are significantly different between BF and sketch conditions for each of the three participants.

Figure 1(a) shows the normalized trends of cognitive activity in sketching and BF sessions for each participant. Every node of the trend line represents the total number of cognitive actions in a 5 minute interval.

The trends in the normalized cognitive activity fluctuated in both sketch and BF conditions for all participants, Figure 1(a). We applied 2nd order polynomial trend lines to obtain the average trend lines of the activities, Figure 1(b). The reason for choosing 2nd order polynomials rather than a linear trend line is to demonstrate the effect of fluctuations in the average trend lines. We obtained higher R^2 values when we applied polynomial trend lines.



(a) (b)

Figure 1. (a) Normalized values of cognitive activity over time, (b) polynomial trend lines of the activity

A similar pattern was observed in the polynomial trend lines of the normalized cognitive activity for the three participants, Figure 1(b). For A1 and A3 the rate of activity in BF sessions (dotted lines) starts at a higher rate and after around 15 minutes drops below the rate of cognitive activity in sketch sessions (continuous lines). For A2 a similar pattern was observed; after 30 minutes the rate of cognitive activity in BF session drops below the rate of activity in sketch session, Figure 1(b).

4.2. PERCEPTUAL ACTIONS

Second order polynomial trend lines applied to the normalized perceptual activity over the 5 minute intervals are shown in Figure 2 for the three participants. A common pattern was observed: perceptual performance in the BF condition dropped below the perceptual performance in sketching condition. For A1 and A2 the rate of perceptual activity in BF sessions starts at a higher rate and in the second period of the sessions it drops below the rate of perceptual activity in sketch sessions. For A3 the perceptual activity in BF condition dropped quickly and then increased towards the end of the session. Different perceptual performance trends were observed for the three participants.

The last two columns of Table 5 show the magnitude of the variance in normalized perceptual, functional and evaluative activity values between the first and the second periods of the sessions. The perceptual activity increased in sketch conditions (positive sign in magnitude of variance), while it decreased in BF conditions (negative signs) for the three participants.

4.3. FUNCTIONAL AND EVALUATIVE ACTIONS

Figure 3 shows polynomial normalized trend lines of the functional and evaluative activities in the sketch and BF conditions for the three participants.

Functional activities of the three architects are decreasing from first period to the second, in BF and sketch conditions (except for A3 where there is no change in sketch condition), Table 5, and functional activity performance in blindfolded condition drops below the performance in sketching condition, Figure 3(a). The magnitudes of the variances in functional activity are significantly different between sketch and BF conditions, for A2 and A3, however not for A1. As a result, functional activity significantly dropped for A2 and A3.

A common pattern was observed in polynomial trend lines of the normalized evaluative activity for the three participants, Figure 3(b); evaluative activity performance in blindfolded condition drops below the performance in sketching condition. The evaluative activity is increasing from period one to two in sketch and BF conditions, for the three participants. The variance in evaluative activity of the three architects from period one to two is significantly larger in sketch conditions (4, 4 and 5) compared to the BF conditions (0, 2, and 0).

4.4. SUMMARY OF THE RESULTS

In the blindfolded condition participants start with higher rates of cognitive activity in the first period of the sessions, and then the rate of cognitive activity drops below the average towards the end of the sessions. In the sketch condition this variance in cognitive activity is less, meaning that there is relatively more steady progress and activity compared to the BF condition.

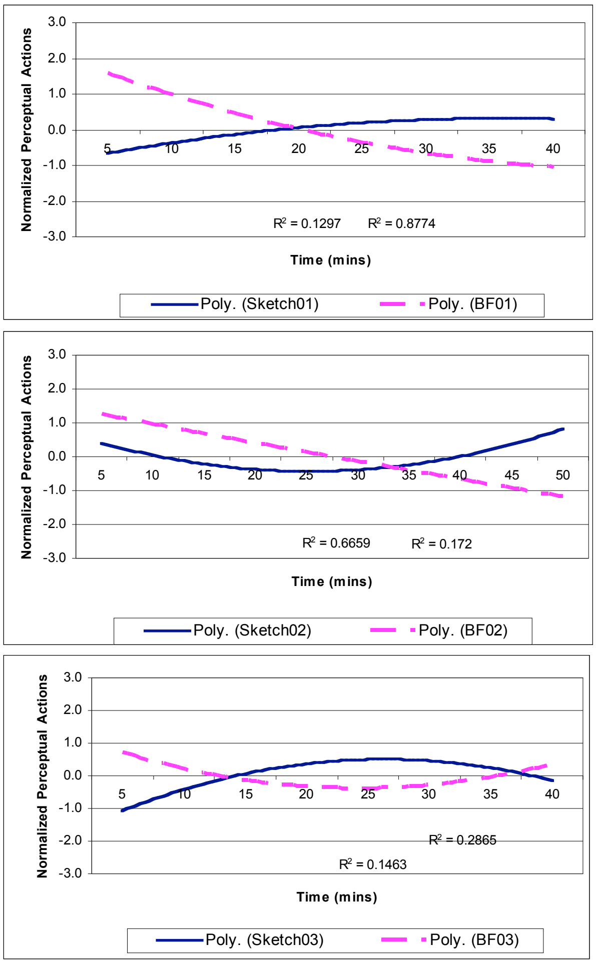


Figure 2. Normalized trend lines of perceptual activity over time

TABLE 5 Perceptual, functional, evaluative activity variances from period one to two

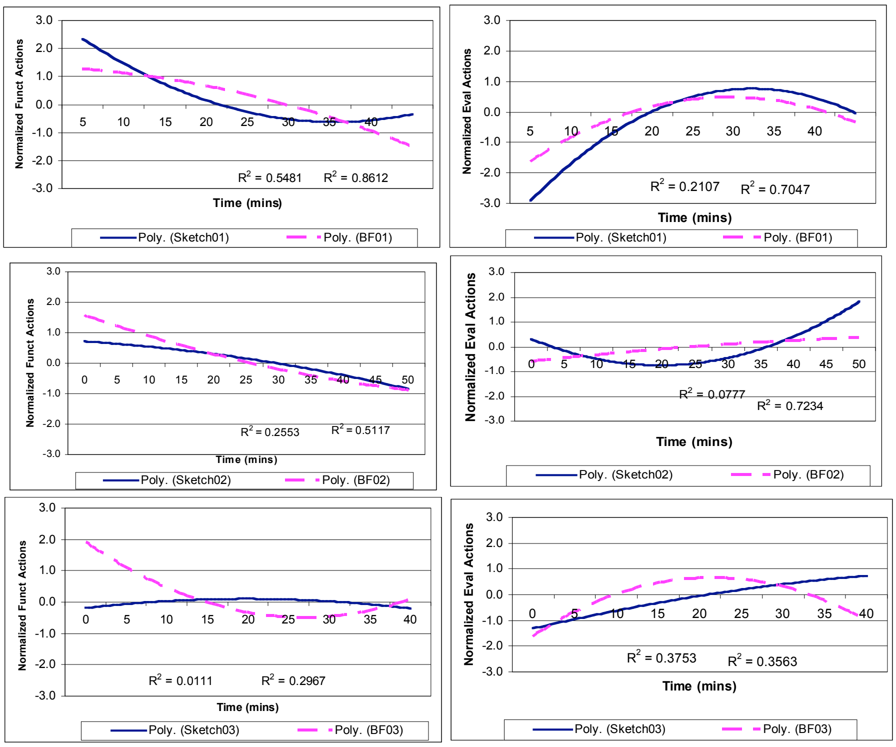
Perceptual Action Category		Normalized activity values		Magnitude of variance	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	-1.0	3.0	2	-6
	remaining	1.0	-3.0		
A2	first 20 mins	-0.1	3.7	0	-7
	remaining	0.1	-3.7		
A3	first 20 mins	-2.0	-0.1		
	remaining	2.0	0.1	4	0
Functional Action Category		Normalized activity values		Magnitude of variance	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	2.4	2.9	-5	-6
	remaining	-2.4	-2.9		
A2	first 20 mins	1.6	2.8	-3	-6
	remaining	-1.6	-2.8		
A3	first 20 mins	-0.1	1.0		
	remaining	0.1	-1.0	0	-2
Evaluative Action Category		Normalized activity values		Magnitude of variance	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	-1.9	0.0	4	0
	remaining	1.9	0.0		
A2	first 20 mins	-1.9	-0.8	4	2
	remaining	1.9	0.8		
A3	first 20 mins	-1.9	0.0	5	0
	remaining	1.9	0.0		

The variance in activity in the three action categories can be summarized as follows:

perceptual activity increased in the sketch condition, while it decreased in the BF condition from the first to second periods;

functional activity decreased in both conditions, the drop of activity in BF condition is significantly larger compared to sketch conditions of the two participants; and

evaluative activity variance is positive and significantly higher in the sketch condition, compared to the BF condition; this implies that evaluative activity improved more in the sketching condition.



(a) (b

Figure 3. Normalized polynomial trend lines of (a) functional activity, (b) evaluative activity over time

5. Discussion

If sketching off-loads visuo-spatial working memory then the cognitive activity in the blindfolded condition should decrease as the design session progresses. We observed that in the second period of the BF sessions the overall cognitive activity dropped below the average and remained there. We also observed significant differences between sketch and BF conditions in the variance of the cognitive activity from the first to second periods of design sessions.

The variance from the first to second period in overall cognitive activity is negative and larger in BF conditions of the three participants than in the sketch conditions. We assume that the drop may be due to the higher cognitive demands of visuo-spatial tasks in working memory when the task is carried out using mental imagery only. Externalization of the visuo-spatial relationships inherited by the imagined objects/things may be reducing the visual reasoning required in design. The drawings/diagrams enable designers to see and reason about perceived set of relationships. This might be difficult without making the relationships explicit by drawing. Anderson and Helstrup (1993) found that sketching does not add significantly to imagery-based discoveries using mental synthesis. In that study the mental synthesis tasks given to the participants involved mental combination of separate simple figures and what was studied was the perception of what the synthesized image looked like using their imagery alone. The range of visuo-spatial tasks performed by the subjects in that study appears to be quite different to blindfolded architects, aiming to design a residential house. Verstijnen et al (1998) conducted similar experiments with industrial design students requiring imagery operations such as synthesis, manipulation and inspection of relatively simple figures. They found that sketching usually was needed if the operations could not be done within mental imagery alone, or if the operations were much easier to perform externally. In a following study Kokotovich and Purcell (2000) conducted experiments with designers and non-designers and obtained results similar to Anderson and Helstrup (1993). In that study the tasks given to the participants were hypothetical small scale design problems, the complexity of visuo-spatial reasoning were somewhat similar to what our blindfolded architects had to deal with. Kokotovich and Purcell (2000) indicated that designers were able to effectively use drawings for creative discoveries while non-designers were not. This result emphasized the importance of experience in utilizing drawings as a means of providing useful cues for thinking and problem solving. Similarly in our study use of sketches was an important issue as a means of thinking and visuo-spatial reasoning during designing. In the blindfolded condition, our expert architects accumulated large amount of visuo-spatial information in the first 20 minutes of the design sessions. Not being able to externalize this information during the progress of designing could have produced a load on participants' thinking. Possibly the reason for drop in overall cognitive activity is this cognitive load.

The results show that sketching improves the perceptual activity over the timeline of the activity (see positive values in magnitude of variance in Table 5). However in the blindfolded condition perceptual activity decreased due to cognitive load from first to second period in the design sessions. VSWM literature supports this finding, where cognitive load is produced due to using the resources of executive functioning (Baddeley et al. 1998). Then why does perceptual activity use up more executive functioning? This is probably related to the difficulty of retaining images in mental imagery. Once the mental images are generated they fade away quickly (Kosslyn, 1980). Even though the images fade away, they can be retrieved from a temporary storage and regenerated again, however this mechanism needs attention, which means executive functioning (Pearson et al. 1999).

In contrast to the positive variance of perceptual activity, the variance in functional activity of the architects is negative in the sketching condition, Table 5. The functional activity in the BF and sketch conditions was not progressive along the timeline of designing (except for the A3 sketch condition, where there is zero variance in functional activity). This result implies that sketching does not add to (improve) production of meaning, however it improves perceptual activity. This result also suggests that the cognitive load may be related to perceptual activity rather than functional activity. The visuo-spatial tasks which require executive resources should create the cognitive load, not the concept /meaning formation.

In the BF condition, architects were able to judge, reason about their designs, and evaluate possible solutions. The results show that the variance in evaluative activity was positive, Table 5, from the first to the second period during the BF sessions. Architects' evaluative activity and design judgments were significantly higher in the sketch condition from first period to the second, Table 5. This means that sketching was a better medium for architects' design solution and idea evaluations. We observed positive or zero variance in evaluative activity in both conditions, which implies that there was no effect of cognitive load for this action category. We propose that the cognitive activity is related to perceptual activity, not to production of meaning or evaluation of design solutions/ ideas.

6. Conclusion

We presented the cognitive activity differences of expert architects when they design in blindfolded and in sketching conditions. From the first 20 minutes of the session to the remaining time in the sessions, the overall cognitive activity in blindfolded condition each time dropped below the overall cognitive activity in sketching condition. We compared the magnitude of variance in the cognitive activity in BF and sketch conditions and showed that the differences are significantly larger in BF conditions. This supports the idea that use of imagery for extended periods could slow down the cognitive activity rate, due to higher demands of cognitive processing in use of imagery alone. During sketching, the cognitive activity rate does not dramatically slow down, possibly because external representations help reducing the cognitive load during the progress of the design activity. We conclude that sketching off-loads the VSWM.

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A ROLE FOR EXTERNAL REPRESENTATIONS IN ARCHITECTURAL DESIGN?

The Influence of a Virtual Office Environment and Early 3D View on Design Activity

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Abstract. This paper discusses the role of external representations in architectural design. In particular, it evaluates the influence of a virtual office and early 3D view on the design activity. Our results show that the virtual office influence volume creation. 3D appears to be an effective means of evaluating volumes, enabling a number of iterations of quick checks. The constraints linked to the existence of a 3D scale model provide a set o external rules structuring the design activity and leading to a different strategy. On the other hand we observe two different strategies of design superposition, an incidental one in the paper/pencil environment anda more integrative one in the virtual office environment.

1. Introduction

Is it possible to assist architectural designers from the first stages of their design activity? And if so, what changes can we expect in that activity? These are the questions we pose in regards to a new-generation assistance system, based on the combined technologies of a pen computer and an interactive horizontal information system intended to provide the designer with several real time representations composed from his/her early freehand sketches.

Despite the abundance of design assistance tools on the market, architects generally start projects with pencil and paper, and only transfer their work to a computer at the end of the process, in order to finalize the presentation. That means the bulk of all design work is essentially carried out using conventional media (Goel, 1995; Schweikardt and Gross, 2000). According to these authors, this choice can be attributed to the fact that digitalised tools require a high level of precision and no ambiguity, and those factors hamper the freedom and abstraction necessary in early phases of the design process.

Our approach aims to understand the activity of design in terms of the organisation of the design process as a system that includes the interactions between the designer and the resources in the environment, and the role of the sketch as an external representation in the design activity. By focussing our attention on the processes by which the designer exploits internal and external resources, we wish to extend the unit of analysis to the architect's design office, including the architect, the instruments he or she uses and the functional relationships between the elements involved. More specifically, our objective here is to understand the influence on the design activity of a 3D scale model constructed in real time from digital sketches drawn using a virtual design desktop as compared to a pencil/paper environment.

Several analyses of work have highlighted the determining role played by artefacts on activity. These artefacts are more than just peripheral aids to the cognitive process. They amount to a form of external representation and acquire the status of cognitive tools, of environmental resources for the action (Hutchins, 1990, 1995). External representations are resources for the action on the basis of their properties. According to Zhang and Norman (1994), these properties are diverse. They act as memory aids, carry information that can be directly perceived and used without being interpreted and explicitly formulated, anchor and structure cognitive behaviour, and change the structure of a task by making it simpler.

1.1. THE ROLE OF THE SKETCH IN THE ARCHITECTURAL DESIGN PROCESS

In the field of architecture, the act of drawing has often been considered by architects as a versatile tool, suitable for all styles and all compositions. Representation on paper offers great clarity to the design. According to Graves (1981), the tension of the lines on the paper has a pregnance that describes possibilities that could not be imagined in thought alone.

The importance of representations using paper is also underlined by Lawson (1997), for whom the pencil/paper drawing mediates and facilitates the design thoughts and ideas which emerge as a result of that interaction. Through drawing the designer thinks about what is being represented.

1.2. DIFFERENT TYPES OF REPRESENTATION

In a more global understanding of the design process, various research shows that designers, by means of different types of drawing, produce different representations to satisfy different objectives throughout the design process (Purcell & Gero, 1998).

On the one hand there are representations that act as problems to be solved, especially in the early phases. These will not necessarily be used throughout the design process but rather to understand the problem. They can take several forms: drawings, textual annotations, notes, colouring, positioning and size of objects, and their meaning may be vague and fluctuating. They are the result of the externalisation of knowledge and the strategies used by the designer.

On the other hand there are representations that act as solutions, especially once the design process is well underway, in the later or final phases. The main aim of the designer in producing his/her representations is to develop them into a final product. This type of representation is intended more to communicate and share the underlying ideas behind the design.

However few tools take into account these different types of representation in certain phases of the design process. Most current design assistance tools take into account only the representations that essentially serve the solutions.

We argue that sketches play a role as external representations in the design process. Externalisation serves as a recording of mental effort, rather than being "vaguely" present in the designer's memory, which eases the difficult tasks of thinking about one's own thoughts (Bruner,1996). Externalisation thus embodies thoughts and intentions in a form that is accessible to the thinking process.

2. EsQUIsE and the Virtual Office environment

Few existing technological systems enable fluid and rich interactions between a real environment and a virtual environment. Augmented reality, augmented virtuality and mixed systems are all concepts intended to fuse the real world and the augmented world. In this orientation, where the fluidity between worlds is in question, the movement toward invisible technology and information appliances (Norman, 1999) strikes us as interesting. The axioms defined for these technologies are as follows: - *simplicity:* complexity must remain at the level of the task, not at the level of the tool, the technology must be invisible; - *versatility:* appliances must be designed to encourage new and creative interactions; - *pleasure*: tools must be pleasant and entertaining.

This invisible technology movement is expressed in the framework of the virtual desktop and the EsQUIsE system (Leclercq and Juchmes, 2002): a system for assisting architectural design at the sketch stage, in which the centralised information processing unit entirely disappears from the view and awareness of the user. This software programme is a prototype for the capture and interpretation of architectural sketches. The development of this tool is based on two main ideas: on the one hand to enable the architect freely to create his/her building from digitalised sketches and on the other hand to provide a series of aids for evaluating a series of design aspects. The central unit is invisible so as not to disrupt the architect's creative flow.

In size and shape the office is similar to a traditional horizontal drawing table. The stylus is similar to a normal pencil, Figure 1.

Figure 1. Virtual Office Environment

The EsQUIsE software programme consists of both a graphic input module and an interpretation module, and enables the construction of an architectural model of the building intended to feed into a series of evaluators, including a 3D scale model extruded in real time on the basis of plans. For a more complete description, see Leclercq, (1999, 2004), Leclercq & Juchmes (2002), Juchmes et al. (2004) and Safin et al. (2005).

The interface of the software programme is shown below (Figure 2)

The 3D scale model is constructed in real time. The tracing papers must be arranged consistently in the tracing paper zone to make up the storeys. Only the black lines are interpreted by the system. Coloured lines act as annotations and decorations. Any tracing paper that contains at least one black line constitutes a storey in the scale model. Tracing papers containing only coloured lines do not form a storey: they form a "decorative" tracing paper on the scale model. Finally, all tracing papers containing black are interpreted, with no possibility of hiding them. It is therefore not possible to have two versions of the same storey without the scale model displaying both tracing papers.

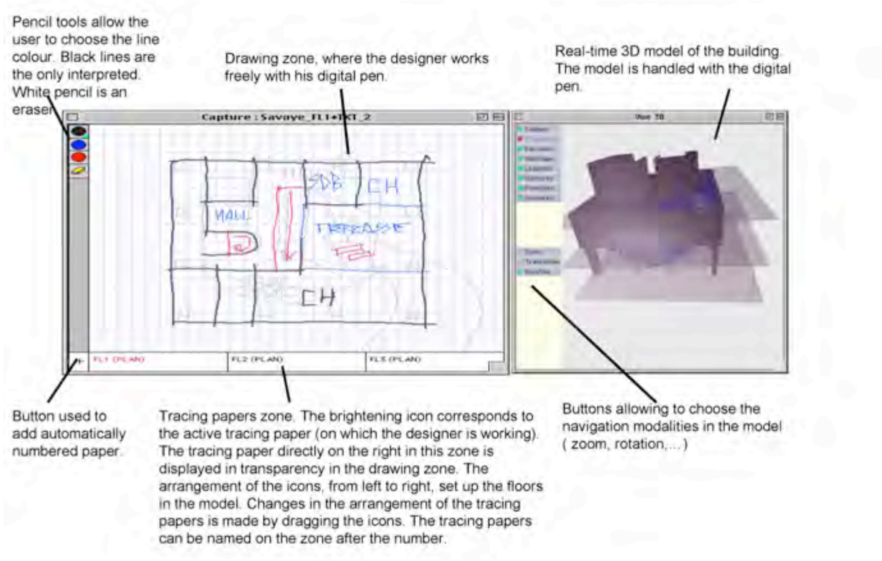

Figure 2. Interface

3. Evaluation of the virtual desktop and EsQUIsE software

3.1. PERTINENT ISSUES

Our objective is to understand the influence of the virtual desktop and the environment of EsQUIsE software on design activity. We proceed by comparing this approach to the conventional pencil and paper approach. The focal point of our interest is the use of a 3D scale model formed from the architectural designer’s plans. This leads us to raise questions concerning two main areas:

- *Use of cross-sections, elevation and et perspective*: What is the real time used for a 3D scale model? To what extent, can it replace the use of drawings of volumes and vertical perspectives?
- *Design superposition*: We aim to better understand building design in terms of volume, how the various storeys of the building are designed,

and particularly whether or not producing a scale model in real time influences design of storeys in relation to one another.

A number of variables were analysed.

- The number of cross-sections, elevations and perspectives
- The time organization involved in designing the various storeys of a building, i.e. the moments of work devoted to visual representations of the storeys.

3.2. METHOD

We explored these questions by comparing the design activity of architectural students in two different design environments: pencil/paper and virtual desktop with EsQUIsE software. Our intension was to carry out an in-depth analysis of these activities. In order to complete our data, we consulted professional architects, particularly concerning perspective drawing.

3.2.1 Approach

The same guidelines and the same exercise (see section 3.2.2) were given to the designers. Each activity was observed and integrally filmed from two points of view: face view, which pictured the whole work area; and an overhead view that followed the progress of the drawings. The two design environments are as follows:

- A "natural" environment (figure 3). The designer is given no particular instructions, except the space for carrying out the drawing, which was necessary for the video filming. The designer had sheets of normal paper, a roll of tracing paper, several pencils and highlighters, as well as straightedges, squares and a calculator.
- The virtual desktop for design (figure 4): The designer interacts with the virtual desktop environment, which is running the EsQUIsE software. The program is equipped with a pen and virtual pallet that offers the possibility of using a number of colours. A single evaluator –

3.2.2 Instructions

The object is to take no more than 4 hours to design a secondary technical school for 240 students. There are several types of design requirements for this building:

- software requirements, the roof has to be flat so that EsQUIsE can correctly interpret the sketches to make the scale model[1].
- site and the storey requirements: a landmark tree has to be preserved and a step platform exists.

[1] The scale model is made by a process of extrusion of the plannar elements. In reality the result is 2.5D : the plans are projected vertically and fixed. This means sloping roofs cannot be visualized nor can story height be parametized.

- specific requirements in terms of juxtaposition of surface areas and spaces.

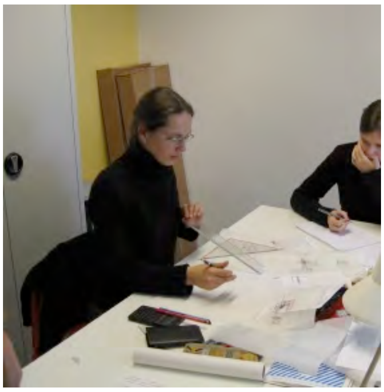

*Figure 3:*A pencil/paper environment

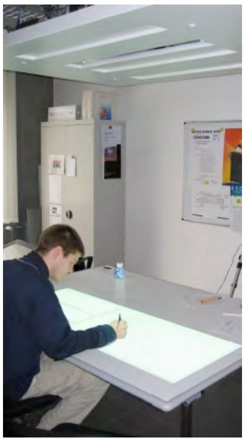

Figure 4: Virtual desktop

3.2.3 Study information processing

The processing consists of a thorough analysis of the video films and the graphic production of the sessions studied (about six hours of video recordings).

<u>*Use of cross-sections, elevation and perspective*</u>

The number of cross-sections, elevations and perspectives were counted. In order to compare the usage of the 3D scale model perspective drawings, we also noted the time that these drawings were made and time where the scale model was being used.

<u>*Design superposition*</u>

A grasp of design superposition was gained by creating timelines that were used to identify sequences of actions involving visual representations of the *storeys* of the building.

- We noted the times when activity involved visual representation of each storey. Each time period was begun as soon as the first line was drawn for that storey.
- We recorded the periods of activity devoted to these visual representations. The activity was measured until the designer started to work on another floor of the building. For simplicity's sake, the time periods were rounded off to the minute.
- The starting time and the period of time spent on the activities were organized into timelines.

4. Results

We initially described the conditions of interaction between the user and the two environments. We then addressed the roles of perspective drawings, cross-sections, elevations, and 3D scale model. The last part of our analysis consisted of describing the conditions involved in designing superposition.

4.1. DESCRIPTION OF ACTIVITIES AND CONDITIONS OF INTERACTION

4.1.1 Paper/Pencil environment

In the Paper/pencil environment, we observe that the designer makes a large number of sketches and uses a large amount of tracing paper, as well as pencils, pens and highlighters. The media (tracing paper and normal paper) are different sizes, especially the tracing paper, which is cut from a roll. The designer also uses a straightedge, square and calculator. The design activity begins by annotating the statement of the exercise and by organizing building design, mainly in terms of floor areas: the areas of each space and the total floor area of the building are calculated. An initial rough sketch of the building is drawn up on the basis of how the building is laid out around the landmark tree. Outline drawings are duplicated and corrected in the first phases of the design. After deciding the layout of the main areas, these drawings are made into scaled descriptions (scale 1/500) of the building. The following plans are drawn to 1/200 scale. The designer proceeds by trial and error: trial drawings are made of one part of the building, and finalized if the designer seems satisfied with the design of the particular part of the building.

Nevertheless, there is frequent backtracking and modification of parts of the original conception.

This part of the activity might be described as a “waterfall” approach: each new requirement encountered or new idea developed engenders a new design for that part of the building. The repercussions are then evaluated in relation to other areas: first, those that are closest and then those that are the furthest from the area that is planned, including other storeys. This evaluation can produce new ideas or restraints. In a sense, the restraints are propagated throughout the overall design.

The same process takes place with each of the numerous detailed plans. When necessary, separate plans are made (e.g. classroom and cafeteria/infirmary). Every decision made is propagated throughout the general plan.

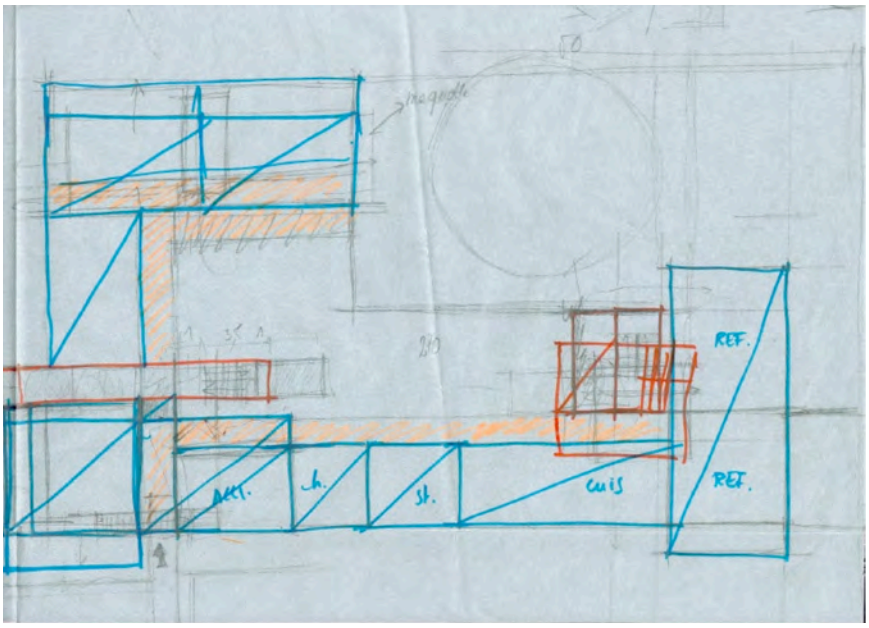

Figure 5: Ground floor plan, scale 1/50

The designer concludes his work with a perspective drawing of the building, in order to check volumes. We note that after the plans were finished that the administrative areas, secretary services and principal’s office, had been forgotten.

4.1.2 Virtual Office environment

In the virtual office, the designer has a different sort of medium: virtual tracing paper. The designer can change the size of the window for the virtual tracing paper, but cannot the size of each tracing paper. The tracing paper is "attached" together, and it is not possible to translate changes in one drawing in relation to another. A single type of electronic pen is available (no highlighters…). Nevertheless, it appears to be very simple to use the tracing paper (one click) and superposition order is also as simple to modify by dragging and dropping tracing paper icons.

In carrying out this activity, the designer mainly uses the red colour for the electronic pen. Black is the only colour interpreted by the software, and it is only used for finalizing the plans. This results in a sort of specialization in the virtual tracing paper:

"Rough drafts" are red. They are the exploratory plans. The lines superimpose and are rarely deleted.

"Finalized plans" are black. These plans appear to be more carefully done than the rough drafts: the lines are straighter, each line represents a wall, and each wall is represented uniquely by a line. The designer frequently uses a digital eraser on the virtual tracing paper.

The designer waits until the end to annotate "finalized plans" with red colour.

This phase of activity also begins by creating a collection of information for organizing and planning the building: the "Base Plan". In the beginning, this plan contains the layout of the various areas. It is used continually throughout the design process, with functional information about the whole building being added.

The building shape is rapidly determined on the basis of the areas needed for each floor. The basement level is smaller than the ground floor and the upper storeys. Initial assumptions are made about the layout of desired spaces on each floor, and the overall "footprint" of the building. The next step is a 3D model of the building, which is primarily used to judge its situation within the available space and to check the shapes of structure volumes.

The designer continues by trial and error. Nevertheless, the decisions often involve several storeys. For instance, elements like a hallway placement may be similar on each floor.

4.2. USE OF CROSS-SECTIONS, ELEVATIONS AND PERSPECTIVES[2]

4.2.1 Occurrence of cross-sections, elevations and perspectives

Whereas the pencil/paper involved eight cross-sections and elevations, and two perspectives, the virtual desktop user made no vertical or volumetric projection.

4.2.2 Use of perspective in the pencil/paper environment

On the basis of our interviews with professional architects, we can describe a number of uses of perspective drawings in the initial phases of design

- Checking the volume perspectives of drawn plans;
- Creating a volume that can serve as the basis of design for the plans;
- Communicating a project design to clients or partners.

4.2.3 Use of the 3D model in the virtual office environment

We observed that the scale model is used in association with the drawing of various sorts of visual support, particularly for plans of the various storeys of the building. On the other hand, exploration of the scale model is only carried out on multiple visual representations during this work phase. We will return to this observation in the following section. It therefore appears that the scale model has an organizing impact on the work. The ways and means that the work is organized is partially a result of the real time presence of the model.

4.3. DESIGN SUPERPOSITION

In looking at the question of superpositioning in the design, we drew up timelines (figures 7 and 8). The vertical axis shows the various storeys of the building, and the horizontal axis shows the time in minutes. These lines show the sequences of design activity for the various storeys, in other words, the time periods during which the architect is drawing on the plan of one of these storeys. In order to link use of the 3D scale model and the perspective drawings, we noted these sorts of visual representations on a separate line[3]

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[2] The plan is an overhead 2D view. The cross-section and elevation are two sorts of 2D drawings that represent the vertical aspects of the building. Te perspective drawing is a two dimensional drawing representing a 3D shape.

[3] Given the fact that the scale model is not drawn directly, the time spent on the scale model is the time when the designer is actually working with it.

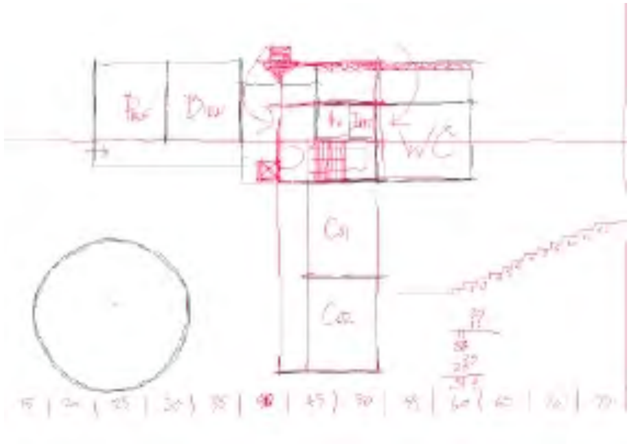

Figure 6: Last version of the ground floor in the Virtual office approach

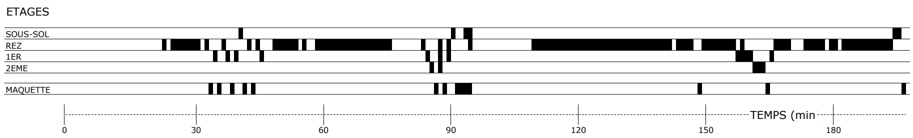

Figure 7: Timeline for superposition design in the pencil/paper environment

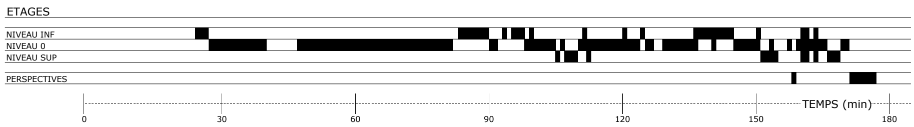

Figure 8: Timeline for superposition design in the virtual desktop environment

These observations enable us to draw a number of conclusions:

- The organization of the two approaches is different. The pencil/paper work is characterized by more or less parallel activity on the different storeys. The virtual desktop work is carried out on the ground floor, punctuated with moments of work on other floors.
- Using the virtual desktop, design superposition is organized around the 3D scale model: there is work done on each of the floors during the time that the model is being explored. Further, we can observe that the moments when the scale model is being built are the *only* moments when work is done on the storeys and the basement level. The work is

done on the ground floor and the other floors are only developed in order to build the scale model.

- The virtual desktop only uses one virtual tracing paper for each of the storeys and the basement level. On the other hand, a number of tracing papers are used for the ground floor. The tracing papers for the storeys are finished tracings, whereas on the ground floor both finished and rough plans coexist.

The relative amounts of time spent on each floor depend on the work being carried out. The ground floor accounts for the bulk of work in both approaches, but the activity of designing the storeys is significantly different, as seen in the following figures.

In both approaches, the tracing paper called "ground floor" (or level 0) is the base floor on which the designer spends most of his time. The proportion of time spent on the other storeys is clearly less when using the virtual desktop, which also has one more storey than the pencil and paper version. The strategies consequently differ in terms of breaking down the work to be done. We will touch on this point during the Discussion section below.

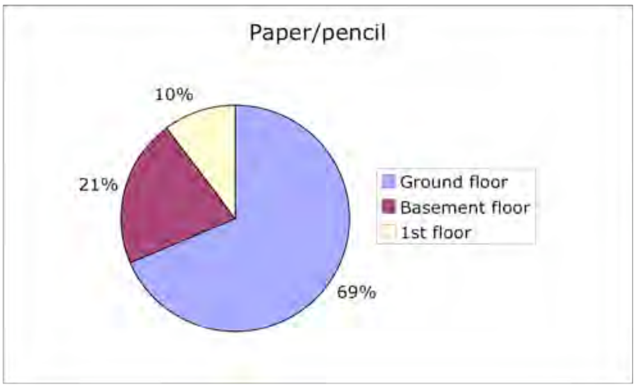

Figure 17: Proportion of work time using pencil and paper

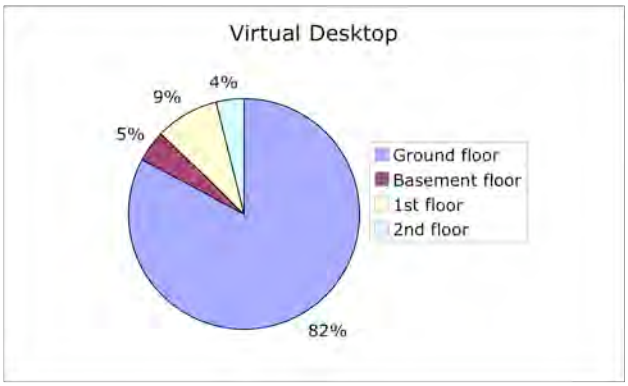

Figure 18: Proportion of work time using the virtual desktop

4.4 TWO STRATEGIES OF DESIGN SUPERPOSITION

We can describe two different strategies of design:

- One is an "incidental" strategy, which takes place in the pencil/paper environment. The information is organized from the outset, but is more strongly focussed the layout of spaces in a plan than on the layout of spaces by floor. The central element is the graph of juxtaposition. This layout of spaces-functions by floor is developed on the basis of trial and error, with the modification of one storey creating a new restriction for the designer. The creation of a space on one floor requires the designer to take into account the implications of that change for each of the other floors. This operation calls for handling and superimposing a number of floor plans.
- The other is an "integrative" strategy, which takes place in the virtual desktop environment. The bulk of the work is carried out on the ground floor. The floors are designed very rapidly during the moments of exploring and handling the 3D scale model. When important decisions are made in the sketch of the ground floor (particularly in relation to the overall shape of the building), the modifications occur on all floors at the same time, and are then checked in the scale model. Everything occurs as though the ground floor contained all of the information necessary for designing each of the other floors. Decisions made for the ground floor contain information for all the other floors and that information is passed on to the other levels (finalization of floor plans) until some major change is made. The individual details of the other floor plans are added at the end of the design process.
- This approach results in a sort of specialization of the virtual tracing paper. The designer links long phases of work on a single virtual tracing paper, which contains all the information concerning not only the ground floor, but also the other floors. At this point, the virtual tracing paper consists of rough plans, drawn uniquely in red, and therefore not taken into account in the scale model. After work is finished on the tracing paper, a number of floor plans can be reworked to produce "finalized" plans – one per floor – which are drawn in black and interpreted by the software.
- At the same time, the finalization of the drawing has various functions:
- For pencil/paper finalization means making a number of design choices, and putting those choices on a new plan
- For the virtual desktop, the virtual tracing papers are specialized. Finalization means "extending" the building, in other words, extrapolating the choices made on a single rough plan to all of the plans for all of the floors, and adapting these plans as necessary.

5. Discussion

5.1. 3D SCALE MODEL, AND DRAWING VOLUMES

Our observations show that the 3D scale model, constructed in real time, plays an important part in the activity. In effect it seems that the use of the scale model tends to supplant the drawing of cross-sections and elevations, and perspective drawing. This question is important, although we do not feel it is possible to draw definitive conclusions from it: replacing perspective drawing by a 3D view implies that the scale model takes on a certain number of the functions of perspective drawing.

In the virtual office, it seems that it is mainly the function of volume checking that is assisted by the 3D. In effect, the user explains at the start of his/her activity the need to check the volumes of what he or she has produced. The 3D is then used at key points in the activity, when the designer has taken a certain number of decisions concerning all the storeys in his/her building. The 3D appears to be an effective means of evaluating volumes, enabling a number of iterations of quick checks.

Whereas in the pencil/paper environment the perspective drawing is produced at the end of the activity to check the volumes of the building, in the virtual office the 3D scale model is used at three points. Nonetheless, the fact that this scale model is generated automatically and electronically poses the question of the act of drawing and hence the externalisation of thought. As shown by Graves (1981), Herbert (1993) and Lawson (1997), through drawing the designer thinks about what he or she is representing, constructs hypotheses and explores possibilities, and new ideas emerge from this interaction. Freehand drawing facilitates lateral transformations, the sketch being a field of heuristic exploration in which the designer discovers new perspectives for solutions. In effect, as shown by Suwa, Gero & Purcell (2000), unexpected discoveries, and design in general, are favoured by the act of drawing, and the revisiting of items that have been drawn previously. Will removing the act of drawing enable the designer to revisit a sketch in the same way? Is there a difference between attributing a new visuo-spatial characteristic to a previously drawn item by redrawing it or by viewing it?

5.2. THE 3D SCALE MODEL AS AN EXTERNAL RULE FOR DESIGN

In the set of internal and external visual representations (Zhang & Norman, 1994), we can observe that the internal rules are those that are inherent to the activities of architectural design, together with those contained in the brief, appropriated by the architect. On the other hand, using the 3D scale model involves a certain number of constraints: a differentiation between the black lines, which are interpreted by the system, and the coloured lines, which are not interpreted, the need to use only one layer per storey, and the need to draw the interpreted lines "cleanly". The system makes the designer systemise the organisation of his/her drawing activity, in particular the organisation of all the storeys.

Thus, the constraints linked to the existence of a 3D scale model not only condition the modes of interaction specific to using it, but also provide a set of external *rules*, structuring the whole design activity and leading to a different strategy. In effect, the multiplication of trial and error on several layers is incompatible with a consistent interpretation and a useful 3D scale model. The scale model therefore structures much of the design activity, towards the integration and planning of the different storeys.

In addition, this specificity of the layers leads to another form of structuring of the activity. In effect, by concentrating the information concerning the whole of his/her building in a single layer, the designer reduces the problem-space: all the information required for managing a multi-storey structure is included in a single, unique visual representation. This means that the designer views the full extent of the problem directly, which, as Zhang et Norman (1994) maintain, reduces the memory load and structures the activity.

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SESSION FOUR

A diary study in the engineering domain
P.J. Wild, C. McMahon, S. Culley, M. Darlington & F. Liu

A framework for experimental laboratory design experiments
D. Choulier & E. Pena

Content-based design analysis
P. Saariluoma, K. Nevala & M. Karvinen

Entropy measurement of linkography in protocol studies of designing
J.W.T. Kan & J.S. Gero

JS Gero and N Bonnardel (eds), *Studying Designers '05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 181-195

A DIARY STUDY IN THE ENGINEERING DOMAIN

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Abstract. This paper reports on a diary study in the engineering domain. After providing an overview of, and the design decisions behind, the study we report on the interim analysis data of the data. As with all research methods, diary studies have a number of strengths and disadvantages, so we provide some reflections on the use of diary studies as a method for examining the engineers and the engineering domain.

1. Introduction

This diary study is situated within a project concerned with the use of documents by people working in engineering domains. It is concerned with, generating: understanding of engineer's information needs & document access; and requirements for document processing and presentation tools (c.f. Liu *et al.* under review). Our overall concern is with issues such as: how engineers' information needs are satisfied by documents; how engineers navigate through documents to find particular information; the document elements (physical and conceptual) do they use to explore content; types of documents they use; what kinds of information needs documents satisfy.

So far the adoption of a diary study has produced mixed results. The data generated is rich and informative, and the content broadly accords with other studies. There have, however, been issues surrounding the representativeness of the number and type of entries (see also Higgins *et al.* 1985).

This paper continues by providing an overview of: 1) the context of our study; 2) diary studies; 3) interim results from our ongoing efforts to gather and analyse data from diarists; 4) reflections on the nature of diary studies.

2. Information Content and Documents

Current information search and retrieval methods provide the means to return candidate documents as potential sources of the information being sought. However, they usually leave the user with the task of exploring the document content unaided in the search for the information itself. It becomes necessary to find ways of identifying which from a set of available, relevant documents are useful, and which element of information in a useful document will provide the most satisfactory information. It is necessary, too, to find means how to access those document elements effectively. Furthermore, we need means by which judgements can be made about a document's provenance (that is factors such as authority, veracity, accuracy, timeliness and suitability for a given task).

In Lowe et al's (2004) study engineers reported that 20% of their time was spent "searching and absorbing information." Adler et al (1998) for example, suggested that 23-80 per cent of the working week was spent reading documents. Further to this they found that people approached reading a document in different ways, including skim reading, reminding, reading to appraise critically etc.

The project has three heavily interrelated project strands concerning themselves with: the nature of documents and novel ways that they can be decomposed into meaningful elements (Darlington 2005); computational representation and manipulation of existing and future engineering documents (Liu *et al.* under review); and the way that engineers think about and use documents (Wild *et al.* under review).

In this work we are undertaking research to understand information user need and document 'characteristics' and the impact of these on information provision to engineers. However, there have been continuing difficulties with getting access to study real engineers in real-world settings (c.f. Subrahmanian *et al.* 2004). Time is often cited as one of the main reasons why subject participation is not forthcoming. Thus, a diary study was adopted because it was considered less intrusive than experiments and protocol studies, and more novel − to participants − than surveys and questionnaires. An added benefit is that the diary study could generate instances of document usage as reported by engineers.

3. Diary Studies

Diary studies are a family of research techniques concerned with self logging of activity by participants. In the literature instantiations vary, depending upon whether the researchers' predominant concern has been with generating predictions of behaviour (e.g. Ericsson *et al.* 1993), understanding behaviour (e.g. Adler *et al.* 1998) or with (design) intervention in a problem situation. The complexity of the diary formats has also varied, from a simple form (Date, Time + free text box), through to something more involved, which is akin to filling in multiple instantiations of a questionnaire. Diary studies have been used in a variety of domains and disciplines, for example in design of artefacts or treatment of pain occurrences. However, their use in design-oriented disciplines has been largely in Human-Computer Interaction which reports over thirty diary studies undertaken on general populations. In contrast only two diary studies of designers or engineers have been found (Aurisicchio *et al.* 2003, Dorst and Hendriks 2001).

Diary studies have been undertaken in large range of domains. However, the downside diary studies is the lack of methodological guidance. Some pragmatic advice is given by Rieman (1993) and Corti (1993), but little is said about deeper design decisions. Diary studies are methodologically and philosophically ambiguous, and thus the simple statement that we did a diary study is not enough; exploration of the design decisions taken is also needed.

4. The Diary Study Design

Our first concern was with the scope of the diary study and whether we focused solely on documents or whether we considered some aspect of context through the notion of an information need (Wilson 1981). Focussing only on documents would miss much of the important context or the activity that a document is being used for. However, focussing solely on information needs alone would not be satisfactory and would move us away from the focus of work which is document navigation and usage. Hence our diary entry has two parts. The first is the Information Need, which asks questions about the activity being undertaken, the information been sought and the activities that were undertaken to do this? The second part is concerned with Document Access and Use. It requests detail about the document 'type,' why the participant read the document, who 'owns' the document and what further actions where taken. Tables 2 and 3 provide an overview of the questions asked in each part of a diary entry. Each Information Need can potentially cross reference one or more Document Access and Usage forms. In practice we have found the overwhelming number of information needs correspond to a single document.

The next design issue was the nature of the information being elicited. Our motivation with the diary study was to elicit information about instances of document access and use and their corresponding information need and activity. A range of diary study instantiations exist gathering either qualitative or quantitative data or a mixture. At one extreme, the use of a date and time field with a blank sheet provides little structure for participants to respond. We suspected that in the context of engineer's time constraints this would result in too little information being filled in. Feedback from our pilot study suggested that more structure rather than less was needed. At the quantitative extreme the user is asked to fill in a form that allows no deviation from set categories. This option allows the analysis of the data with statistical measures, and may have the benefit that more entries are filled in. However, the problem with this is that too little is known about information needs and documents in engineering to construct such a rigorous elicitation structure.

In the end a compromise was made between the two 'extremes.' Some questions (e.g. document type, document elements used, archives searched) have categories that participants tick, with an option to provide alternatives. Other questions (e.g. the information need, the activity, what follow-on actions occurred) were left open in format and the participants were responsible for describing their own behaviour.

The suggested advantage to this compromise format is that it balances the risks of either meaningless quantitative data or too little relevant qualitative data being recorded. Additionally, as a safeguard against the number of entries being too low the entries gained would still be rich and interesting enough to refine into a number of scenarios for discussion with engineers. It also allows the data to be analysed in the light of the other project streams (i.e. document decomposition and computer tools). For example, the qualitative answers give insight into the nature of type of searches being undertaken and the quantitative answers can help us to prioritise support in our prototype software tool [1]for certain documents types, search patterns and reading patterns. Thus, the diary design collects qualitative and quantifiable information. Additional analysis is being undertaken to code qualitative responses (e.g. the information need; and activity) however, this is a difficult task due to the diversity of responses.

The next issue is whether participants fill in the entries in real time or not. Aurisicchio et al (2003) were heavily concerned that diary entries be undertaken in real time. But in general, little is said in other diary studies as to whether diarists filled in diary entries in real time (e.g. Adler *et al.* 1998, Ericsson *et al.* 1993, Rieman 1993). We encouraged diarists to fill in the diary in real time; however our expectation from the pilot was that they would not do this all the time. Hence, we asked respondents to indicate when they had filled in the entry. Overall the data to date (see table 1) shows that the largest category for filling in the diary was immediate.

[1] Engineering Document Content Management System (EDCMS)

TABLE 1. When the diarists filled in their entries

Immediate	1-10 mins	10-60 mins	Over 1 hour	Over 1 day	No response
39.81%	3.88%	12.62%	19.42%	13.59%	10.68%

The next diary design issue to be addressed was the 'duration' of the study. Most instantiations of diary studies have asked participants to fill in entries everyday for one or two weeks. In studying designers we face a subject population with time constraints, and gaining participants can be difficult. The intensive mode of entry-making traditionally used would not be available. However, several engineers have agreed to one-off diary days, and several others have offered to undertake several diary days over a period of several months. We are also working with several organisations whose needs and interest align with our own in order to find further participants. However, as with all forms of empirical research with people we acknowledge that there may be a self selecting element in our population that are interested in this issue because they see it as being pertinent to them.[2]

The final issue is how we elicit background and contextual information from participants. The most developed form of diary study is the Diary Interview Method (Corti 1993, Rieman 1993), which combines diary entries with an interview to discuss entries and clarify the analysts understanding and gather contextual information. Our study is a modified diary-interview method (c.f. Corti 1993, Rieman 1993, Zimmerman and Wider 1977). The interview has been 'replaced' by a survey, with follow-up contact for clarification or responses and diary entries. This choice came about for three reasons. The first is that there was considerable overlap between the questions that would have been asked in an interview and those in the existing survey. The second is that we can compare our diarists and the engineers surveyed in the previous application of the survey (Lowe *et al.* 2004). The final reason is that we felt that filling in the survey would take less time for diary participants than arranging and undertaking an interview.

4.1 FORMAT AND QUESTIONS

The diary is available as a paper based form and as a MS Word form. To-date diarists have been evenly split in their preference for paper or electronic format. There appears to be no difference in length of answers or attention to detail in either the electronic of paper based format. A detailed set of

[2] This is not an issue that can be removed in controlled situations such as experiments (see Orne 1965)

instructions were given as well as a number of sample entries. As mentioned the two forms have a number of questions. Tables 2 and 3 list the questions and indicate whether the participant had to enter a free text or check box answer.

TABLE 2. Information Elicited in the Information Need Component of the Diary Entry

QUESTION	INFORMATION TYPE
Name	Free text
Date	Free text
Time	Free text
Time elapsed since activity	Checkbox
Activity being undertaken	Free text
Information been sought	Free text
New or Old Information Need	Checkbox + optional free text
What has been done	Checkbox + optional free text
What document repository has been accessed	Checkbox + optional free text
What cues caused the document to be chosen	Free text
Has the information need been satisfied, and by which document(s)	Free text

TABLE 3. Information Elicited in the Document Access and Use Component of the Diary Entry

QUESTION	INFORMATION TYPE
What 'type' is the document	Checkbox + optional free text
Why did you read the document	Checkbox + optional free text
What is the document format (electronic or paper based)	Checkbox + optional free text
Who does the document belong to	Checkbox + optional free text
Time taken to use the Document?	Free text
What elements of the document helped you find the information sought	Checkbox + optional free text
What sort of elements would help	Checkbox + optional free text
What did you do with the document	Checkbox + optional free text
Has the document satisfied the information need, and if so how	Free text
Did any other action occur	Free text

5. Interim Findings

Each month of the duration of the diary study we create a copy of the database and freeze the results to date. Even at this interim stage analyzing and presenting the data is useful. In the August 2005 freeze we have collected 46 diary days from 18 participants. This corresponds to 103 Information Needs and 118 Document and Accesses. All participant are trained, trainee or practicing engineers. [3] The next section provides a tangible example of the form of the data that we are obtaining from diarists, whilst the subsequent section provides summary data of a number of questions from the information need and document access forms.

5.1 AN EXAMPLE ENTRY

Box 1 is taken directly from a diary entry by one our participants, and provides an example diary entry from one of our participants. The bulk of it is quoted verbatim from the diary entry, the further particulars are a summary of several responses.

We have developed a provisional coding of these activities. We stress that this is to get a feel for the types of activity that are being carried out, and to help us reflect on whether the activities we are having recorded are 'engineering oriented' enough. When we have enough diary entries a refined coding scheme will be applied by several analysts and cross-rater agreement measured.

TABLE 4. Provisional coding of reported activities

ACTIVITY TYPE	**COUNT**
Analysis	23
Design	15
Testing	02
Learning	11
Meeting others	13
Informing others	14
Planning	03
Documenting	22

[3] The six trainees were involved in a group design project that is renowned for producing industrial quality and contemporary projects

Activity

EMC Testing. A dispute has arisen over a number of comments in a customer Test Report issued 3 months ago. A search of the Test activity Logbook needed to be undertaken to check what was done and recorded to the time of testing. The Logbook has been archived (as paper)

Information Sought

Procedure description of one particular test (there are a number available) from a particular specification document + Old Need due to, The information is needed to clarify a point relating to data recorded in a customer test report already issued to the customer.

Need Satisfied

The Logbook clearly referred to the technical question posed by the customer. As a result a letter was drafted to the customer to explain the point in question as the customer had misunderstood the comments in the test report and a more comprehensive explanation using reference material found in the test logbook was provided. At this time (until customer responds) it is not clear how successfully we have answer the customers questions.

Alternative Action

At this time (until customer responds) it is not clear how successfully we have answered the customer's questions. It may be at a later date we need to respond again to clarify points with the customer.

Further particulars

The documents in question were local and paper based and an electronic file based on the workgroup area. The engineer read the documents to learn and to search for data and found the heading and abstract useful. No other action was taken to store or copy the documents.

Box 1. An example diary entry

5.2 DATA ABOUT INFORMATION NEEDS

Box 2 lists some of the activities reported by participants.

Preparing Agenda for Monthly project management meeting.

Technical information for engineers for reprogramming PLC and commissioning machine

informing engineering colleagues (3 engineers) about modifications of inspection systems

Research into different disabilities to establish the varying levels of use of muscle groups for each types of physical disability.

Creating CAD model

Preparing project capital expenditure justification

external ground exchanges design slinky layout

ground exchanges vertical layout

Business Report market analysis

update status report

prepare for meeting

reviewing Friday's team meeting minutes and preparing list of things to do today

machinery design

Feasibility Study of small scale wind turbine

equipment design

Developing design

Handle design

CAD drawings

Box 2. Sample Participant Activities

5.2.1 Example Information Needs

Box 3 lists a number of example information needs. These illustrate the information that is being sought by the participants. Again we aim to develop a coding scheme for these responses, although we suspect that this will be harder because of the sheer diversity.

CKE diagrams (control systems and new inspection machine)

no. of complaints due to particular farm crop

cost of waste for various products & various stages of manufacturing process

to find customer specs

location dimensions

UK market for renewable energies in general Potential markets council houses brown belt development communities SWAT and PEST analysis

results of a Myers Briggs assessment test needed to review the results of a psychometric test that I took prior to a meeting to discuss learning styles

Search for new companies that use friction stir welding
How to keyword to show that the article contains information on palladium
Composition of steel 4140
general dimensions of main components and distances between components at the rear of the car.
how do I select appropriate bearings
Costs involved? How efficient is it? What conditions are required? What conditions are present at the location of installation? Calculations for design?
past design alternatives suggested
Procedure description of one particular test (there are a number available) from a particular specification document

Box 3. Sample Information Needs

Of the 103 information needs collected 61 were categorised as new and 44 as old, 2 were categorised as being both new and old. What is apparent at this when stage when examining the responses, is that there are difference between the information being sought in new and old needs. Older needs tend to be more focused and concrete in nature, whereas new needs tend to be more abstractly specified or *ad hoc* requests.

5.2.2 Archives Used

In seeking information from documents people searched a number of different archives. We asked participants whether the archives belonged to them, their employer, or were external. We also asked whether the documents were paper or computer based. The results in table 5, if replicated across the duration of the study, supports the view that people still rely on paper-based and personal archives for documents.

We now move onto to present data on the participants' document access and use forms.

We asked participants what 'type' the document was that they accessed. The results are in table 6, additional categories of document type have been recognised, and we expect this to expand as we gain more entries.

TABLE 5. Which document repositories were accessed

SOURCE	COUNT
Not Applicable	05
Personal Archive	43
Computer Based	25
Paper Based	27
Colleague's archive	09
Computer Based	07
Paper Based	03
My employer's archive	24
Workgroup	13
Library	08
Intranet	02
External archive	24
Library external	07
Web search	24
Online database	04

TABLE 6. Types of document accessed

DOCUMENT TYPE	COUNT
Drawing	08
Correspondence	12
Journal	10
Minutes	05
Technical report	04
Management report	04
Standard	07
Numerical	06
Feasibility	02
Supplier information	02
Contract	01
Multimedia	05
Instruction manual	03
Other	61
Interim analysis of 'others'	
Logbook	04
Website	14
Presentation	03
Reference Book	15
Misc	25

Further to these types we have also found the use of document proxies. Perry *et al.* (2001) introduced the notion of a document proxy, whereby one object is used to access another. Their main example was the use of a mobile phone to call someone who would read information from a document for them. Within the diary study we have seen emails and webpages act as proxies for a variety of other documents and applications. In general we expect the situation is made more complex by email also being a carrier for other documents and the open-ended and flexible nature of proxies such as web pages, which stand in for orders, catalogues, product brochures, databases, and numerous other documents and applications. Related empirical studies are investigating this notion of document proxy in more depth (Wild *et al.* under review).

In the document access and use form participants were asked how they read the document. This used an adapted [4] taxonomy of work related reading from Adler et al. (1998). No indication on the form was given whether to provide just one description or multiple reasons for reading the document. However, on over 40 occasions participants gave multiple reasons for reading a document.

TABLE 7. How the Participants Read the Document

READING PURPOSE	COUNT
Skim read	15
Read own text to remind	11
Read to search / answer questions	24
Read to learn	25
Read for cross-referencing	11
Read to assess, edit or critically review text	06
Read to support listening.	00
Read to support discussion	09
Read to search for data *	35
Read to search for image or figure *	14
Other	18
Potential additional categories	
Read calculations Read published text to remind Read to generate data	

[4] Those options marked * where added, and participants we not required to state only one purpose for reading the document.

Each one of these classes of reading is a different task. It would follow that they require different types of support, needing in turn different access mechanisms and tools. For example, the task of reading to support a discussion requires information about subject, pros, cons, existing arguments, etc. These could be viewed as decomposition elements. Therefore the sorts of decomposition elements needed for this task could be different than for other tasks.

A document can be seen as being composed of a number of physical and conceptual elements such as keywords. Our aim was to elicit information about the elements of the document used, and the results are summarized in table 8. What is marked in the responses in the others section is that other physical elements were requested but clearer demarcation of conceptual elements such as Introduction, Summary, etc were not used or requested.

TABLE 8. The document elements used and wished for

DOCUMENT ELEMENT	USED	DESIRED
Abstract / Summary	10	1
Keywords	15	4
Contents list,	14	2
Figure of Table List	5	1
Table or figure caption	8	1
Section heading	24	3
Index	15	0
Search	11	5
NA	27	47
Other	23	6

6. Reflections on the Diary Study

6.1 USEFUL FEATURES OF DIARY STUDIES

A key feature of diary studies is that participants interpret their behaviour and represent it to researchers via a structured format. In general this is done in real time, as the activity is undertaken. Hence, in general, recall effects from filling in a survey at a later date are minimised. The tendency to embellish or distort answers may also be less prevalent than questionnaire based approaches. The problem of recounting how you were taught to do something, rather than how you actually do it may also be avoided.

The data generated in most cases is rich and generally the content of diary entries accords with other studies. Furthermore, the form of the needed information has been used to generate scenarios and requirements for document access and representation tools (c.f. Liu *et al.* under review). This is broadly in line with Rieman's (1993) assertions that diary data provides a useful way of capturing behaviour in the field that can then be used in more empirical and software development settings. However, we have concerns about the representativeness of the data that has been generated.

6.2 IF THIS DATA IS TO BE BELIEVED!

Although we have 48 diary days of data the distribution is disheartening. Twenty-four diary days indicated that they only had one information need. We need to examine this data in relation to the length of time a document was used as in some cases documents used were used over a period of several hours to several days; on others use takes as little as 2 minutes. This goes against previous studies, informal reports from engineers themselves, and our own observations of our own document use (see Adler *et al.* 1998, Lowe *et al.* 2004).

We are not the first to be concerned with the ecological validity of diary data, Higgins et al. (1985) undertook a diary study of phone call behaviour and made comparisons between dairy entries and the actual calls made as recorded on the actual exchange. Their hypothesis that people would under-report phone calls was confirmed. If this phenomena is carried over to diary studies in general we can assume that engineers will under-report information needs and document access. However, it may be that the data shows: 1) the same overall patterns, but lower numbers of entry; 2) the same number of entries, but the wrong pattern; 3) the duration of document use is too low; or 4) duration of document use is too high.

To further address this issue further examination and triangulation of the diary data is being made. The first part is to take snapshots of the data as we collect entries. If patterns of data suggested in the results in Section 5 remain stable across the duration of entry gathering, we can have more faith in the data.

The next strategy is to undertake a range of online and offline observations of document access and use. A computer-based toolset is being deployed with a number of engineers, some of whom are making diary entries. This will allow us to capture data about the number of online documents that they access. We are combining this with paper-and-pen observations of engineers to gather data about offline document usage.

7. Conclusions

Diaries are another way of getting glimpses of engineers' work and information practices. Unlike many other research methods, the data generated, and the richness of diary entries, can be used directly to generate scenarios and requirements for the development of software tools. However, from a research techniques perspective Diary Studies are an interesting methodological beast. As well as having some of the advantages of other techniques, as a hybrid form of research technique they also have disadvantages. Despite this, this diary study has so far demonstrated that we can at least elicit rich and informative information about engineers' use of documents and their corresponding information needs.

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A FRAMEWORK FOR EXPERIMENTAL LABORATORY DESIGN EXPERIMENTS

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Abstract. In this paper, we present a guide for questioning and building concepts during experimental laboratory design experiments. The main discussions are on the nature of the data manipulated by the researcher. Their definitions and the links between them make the skeleton of a representation of part of the research process. An example and results are given to illustrate.

1. Introduction

Different methods have been proposed to study design. Look Akin (1997) and Cross (1999) for a survey. Nether the less, few research methodologies exist to effectively guide research.

Lucienne Blessing (2002) proposed a Design Research Methodology (DRM), which addresses a systematic but mainly descriptive approach with 4 main stages: criteria definition, descriptive studies 1 and 2, and prescriptive study. The definition of (mainly product) criteria is thought important to identify research goals and make the evaluation possible. In descriptive study 1, the building and validation of a reference model containing the factors influencing criteria is proposed. Then prescriptive studies lead to a method or tool, tested and evaluated in descriptive study 2. The process is not fully sequential: activities can run in parallel and iterations are proposed. One main critic we address to DRM is that such a description does not fully explain the emergence of design process hypotheses, models and concepts during research.

In a recent work, we proposed with colleagues from 3S laboratory (Prudhomme, Brissaud & Choulier 2005), to represent / describe another research cycle. Goals are central; they can address the generation of knowledge (academic objective) as well as tools development. The elements of the model are experimentation, observation, analysis, modelling, specifications (of tools), prototyping, development, and use. This is a formal frame inside which we will detail and interpret here some parts of the first elements, from observation to analysis; aiming not only to describe, but to propose a reflexive tool for research.

Siding in situ observations using ethnographic approaches in real conditions (Perry and Sanderson 1998; Vinck 2003; Badke Schaub and Frankenberger 1999; Jagodzinski, Reid and Culverhouse 2000) laboratory observations of designers in controlled conditions has grown in importance during the last 20 years, most of them using the Protocol Analysis technique (Ericsson and Simon 1984; Gero and Tang 2001; Cross, Christiaans and Dorst 1996)

A sequential presentation by Atman and Turns (2001) identifies the following steps:

- Develop a coding scheme
- Choose a problem, in this case a design problem
- Collect protocols from students as they solve the problem
- Code the protocols according to the coding scheme
- Analyse and interpret results

One critic to this simplified presentation is that if stages such as "Choose a problem" and "Code the protocols" are declared, very few guides propose **how to do** even though some authors report their difficulties (Dorst 1996; Gero and McNeill 1998). The segmentation of the protocol itself – necessary for coding – is coding scheme dependant: "… segmentation … is not generated by the data, but based on imposed categories" (Oxman 1995). This article is a tentative to go further. Main issues are to guide the researcher (if possible), to better control the research process, to focus on research goal, and to make experiments comparable and reproducible - a true challenge.

2. A proposed reference data model for experimental design observation

2.1. DISTINCTION BETWEEN ROUGH AND INTERPRETED DATA

We will focus here on one main question: the status of the data a researcher manipulates, and the part of interpretation that is necessary for their definition.

Direct observation can produce "rough" data or observed facts – i.e. data observed without any or few interpretation. In this category, we can report the words exchanged by the designers, their gestures, their body positions, their glances, the marks they make on design objects, any elementary action, the use of their finger or pen to point on an object, the presence of an object, a sound … A first discrepancy can occur during observations. The use, position, adjustments of the recording devices, or simply the attention of the observer, can lead to non observed facts. Nether the less, in laboratory condition, one can infer that such discrepancy can largely be reduced by using appropriate means… But these are not the data used for models.

From these "rough" data and often after their transcription into texts or tables - the corpus - the coding stage aims at extracting processed information. Any taxonomy imposes rough data to conform to pre established categories that have to be exhaustive (any data should be coded), with minimum ambiguity (two persons using a same coding system with its rules should give the same code), and making reference to models as these interpreted data are the elements of models. Some examples: Design Objects become "mediating" (Mer, Jeantet and Tichkiewitch 1995), or "talking" (Fergusson 1992, cited in McGown, Green and Rodgers 1998 and in Van der Lugt 2005), a sentence can be qualified as "propose a solution" (Gero and McNeill 1998; Darses, Detienne, Falzon and Visser 2001, Choulier 2004), a glance as an "attention to another designer", a gesture with a finger as "pointing" …

2.2. REPRESENTING THE WEB OF DATA RELATIONS

Protocol analysis has often been used with single type data or at least with direct links from rough to interpreted data. It seems however pertinent to avoid a complete dissociation between verbal and non verbal data. Akin (1996) Purcell & Gero (1998) and Suwa, Purcell and Gero (1998) are examples where verbal and non verbal data are used for analyses.

The difficulty we encountered in our research lies in the fact that we have been confronted to a more complex situation due to our willingness to both capture much information of different types from experimentation, to refer to notions that are not self evidence in models, and to make the relations explicit for an automatic treatment. The one to one dependence relation from rough to interpreted data was not the common case. One interpreted data can depend upon two or more types of rough data. One rough data can lead to more than one code. Some interpreted data can depend upon other interpreted data…

Therefore, in order to both clarify and explicit our concepts, we propose the image of a web of explicit relations between data (see the example). This type of representation must be understood as a support for the reflection of the researcher, aiding him to capture a synthetic image of part of his own research process. It allows him to control which collected data are effectively used and for which purpose. It helps in defining the entities of the used or emergent models. It is also a good communication tool inside and outside the research team.

3. Illustration

We will give some objectives of the experimentation, the description of the experimental device, the web of data relations and definitions, and examples.

3.1. OBJECTIVES.

We present here an experiment and results extracted from Ezio Pena's PhD. (2005). His thesis gave a frame inside which the experiences had to be defined. The design task had to take place in the conceptual design phase - more precisely a first collective search for potential solutions. In order to investigate the alternation between cooperation on Design Objects (DO) and conversation, a segmentation of the design space into different sub spaces has been imagined. This segmentation has also been inferred from an analogy with remote design where the communication and object sharing are dissociated through different channels. We also intended to collect information of different nature - not only verbal - to capture part of the complexity of the design process, which impacted on the definition and creation of tools for analyse. Finally, the experience had to be short enough and reproduced for consistency.

3.2. DESCRIPTION OF THE EXPERIMENTAL (AND ARTIFICIAL) DEVICE

The device presented in figure 1 defines several types of spaces.

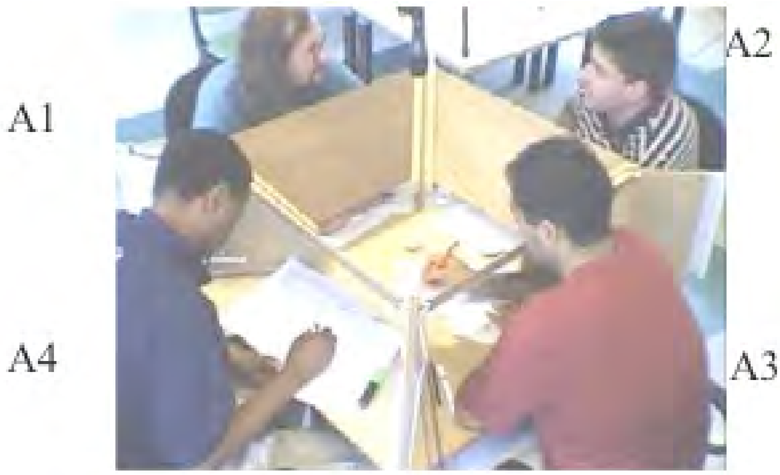


Figure 1. Experimental device for observation of individual and collective spaces

Above this device, the designers can see each other's faces (above shoulders) without any restriction. This functionality was imposed by the need for free conversations, eventually aided by gestures. Contrary to remote design, the glances are natural here.

The table is segmented into individual spaces and one collective central space, visible and accessible from each edge of the table. The separations allow relatively free working in this central space, and passages of sheet papers or any object between central and individual spaces. The designers have been instructed to use these spaces as freely as needed. In particular, they could move, look at any part of the table… the only strict instruction was to use the central space during collective work. In this configuration the position of the eyes indicates possible directions for glances and the separation between individual and collective spaces makes it possible to locate the glances to the different representations.

The video cameras are placed along lines which are intersections of three separation planes (see figure 1). Two opposed cameras are used. For instance, in figure 1, designer A1 and A2 see each other. Designer A3 watches the central space (he can't see his own individual space) whereas designer A4 watches his individual space (he can't see the central space). Both could immediately move their head: up to see A1 or / and A2 (the second camera indicating which), or look at another space. See Pena (2005) for details.

Paper sheets are referenced with a number and a colour code to identify their positions and movements. A microphone with a separate audio recorder is placed above the table to capture the verbal exchanges. Synchronization of the three digital recording devices is achieved by a "clap".

3.3 SUBJECT AND DATA CAPTURE

Designers are mechanical engineering design student. The subject was presented in the form of a contest, which characteristic is to be defined with fixed constraints allowing few (if ever) questions on the problem definition – see Pena, Choulier & Garro (2004). In this sense, it is not an "ill defined" problem. A one hour duration was specified, but with tolerance for finishing. The observers recalled for time at 50 and 55 minutes. Four "identical" experiments were recorded.

A written corpus of the verbal exchanges has been transcribed and the other data capture has been done mainly from videos. We identified instants, each indicating a new event: the creation of a design object, an action on it (with hand, pen or finger), a change in space content (for instance an object moving from one space to another), or a change in an eye position or direction. The duration of a period between 2 events is short, currently 1 to 5 seconds, sometimes 15 to 20 seconds, and up to 60 seconds but rare. The number of periods range from 674 to 977 (977, 674, 774, 730). We note that, since now data have already been subject to interpretation: The linearity of time is broken, a data selection and qualification is done.

3.4. USED WEB OF DATA AND DEFINITIONS

Figure 2 gives an image of the data and concepts used. From rough data, different concepts or/and codes are defined, with dependencies from bottom to top. Each concept is defined for a given period. A small vertical arrow indicates that one data is used thereafter for analyse. Dotted arrows from "actions on DO" are justified by the fact that we never observed actions on DO without attention on DO.

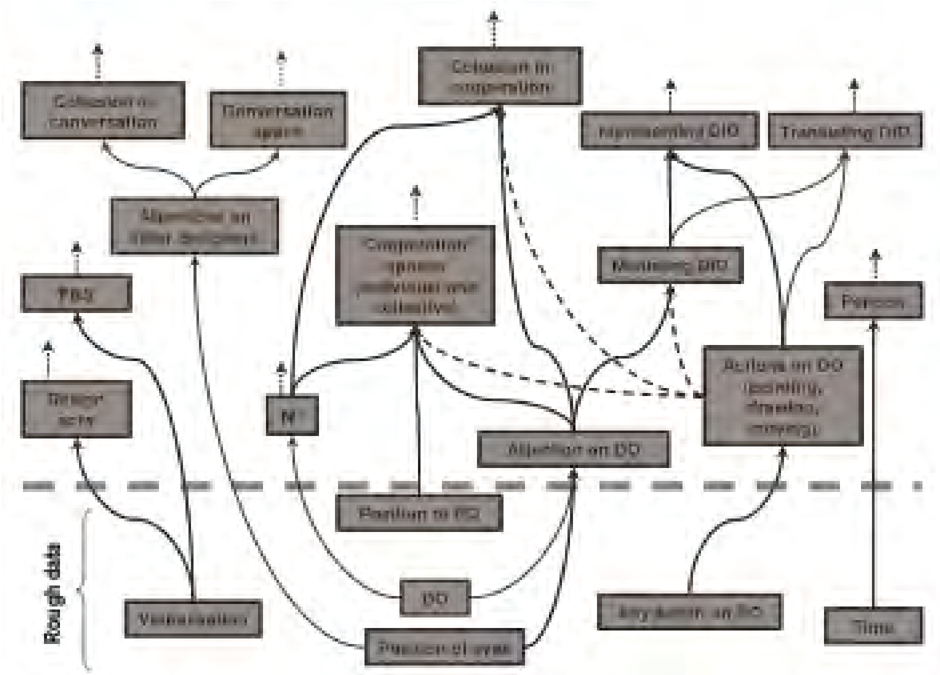


Figure 2. Web of used data in Ezio Pena's PhD. DO means Design Object. DIO means Design Intermediary Object

The definitions of each concept can be done indicating from which previous data it comes.

- Design acts are defined **from** verbalisations (Choulier 2004).
  FBS (Gero 2002) are qualifications of the product, defined **from** verbalizations
- An attention of one designer to another one is found **from** his eyes position **when** he looks at him.
- A conversation space is observed **from** the attentions **when** two designers at least pay attention to each other.

- Cohesion in conversation is defined **from** the attentions on other designers. It depends on the number of designers. See later
- A number is affected to an object **when** this object is seen in the video. An attention on an object is found **when** a designer looks at it **from** his eyes position.
- A cooperation space is defined **when** two designers at least pay attention on the same object.
- Cohesion in cooperation is defined **from** the attentions on design objects when directed to a same object. It depends on the number of designers. See later
- Actions are coded **from** any action on an object. It can be "pointing", "drawing", "moving".
- An object is a mediating object **when** two designers at least pay attention on it.
- It becomes "representing" **when** a designer points on it.
- It becomes "translating" **when** a designer draws.

Note: the terms mediating, translating, and representing are interpretations of the notion of Design Intermediary Objects (DIO) defined for longer design projects; see Boujut and Laureillard (2002)

Of course, these definitions reveal choices we made; they can be discussed. The important fact here is that such a figure reveals the dependencies between the different definitions.

3.5. EXAMPLES OF DATA COLLECTION AND INTERPRETATION

We detail here two instants coming from the same experience. The codification of verbal exchanges into design acts and FBS product description is not described here. This analysis must enable us to differentiate the periods marked by the use of Design Objects from those marked more by the conversation.

3.5.1. Data capture

The capture of rough data is made on excel datasheets (see tables). They synthesise for each instant the direction of the glance, the type of action, the number of the DO, and the space in which this object remains. We must say that completing this real-time operation must be made with rigor concerning the criteria used for detecting a change of configuration – an instant. The choice of these criteria must conform to the research objective. From these datasheets, it is possible to apply an automatic treatment– excel macros here – for determining the other data.

3.5.2. Instant A

Instant A is picked from the corpus of experience N°1. It corresponds to figure 1.

At "00:28:37" (Table 1), the situation is described with 2 actors who discuss and 2 actors who look at different representations. The analysis of the audio and video recording makes it possible to determine that actor A2 (upper right corner of the image) speaks to and looks at actor A1 (upper left corner). Actor A1 looks at actor A2. Actors A3 and A4 work separately, each one on a different object in a different space. The first (A3) draws on the public space (Pb) - DO N°7 - , the second (A4) annotates DO N°8 on his individual space (Pv).

TABLE 1. Data capture, example A, corresponding to figure 1

Moment	Actor	Glance	Action	DO	Space
00 :28 :37	A1	A2			
	A2	A1	Talking		
	A3	DO	Drawing	7	Pb
	A4	DO	Annotating	8	Pv

From this table, one can deduce that (refer also to figure 2):

- There is some attention on other designers (A1 looks at A2, and A2 looks at A1).
- A conversation space exists – it is active.
- A cohesion in conversation can be defined (see later)
- There is some attention on Design Objects
- But the cooperation space is not active because A3 and A4 look at different objects, and on different spaces.
- For the same reasons, there is no cohesion in cooperation, no mediating, representing or translating roles for any Design Object.

3.5.3. Instant B

Instant B is also picked from the corpus of experience N°1

TABLE 2. Data capture, example B.

Moment	Actor	Glance	Action	DO	Space
00 :58 :37	A1	DO		7	Pb
	A2	DO	Talking	7	Pb
	A3	DO	Drawing	7	Pb
	A4	DO	Annotating	4	Pv

At "00:58:21" (Table 2), the situation is quite different. Three actors look at Design Object N°7, in the public space. One is talking, one is drawing, and one observes; he certainly listens too. The other (A4) annotates DO N°4 on his individual space (Pv).

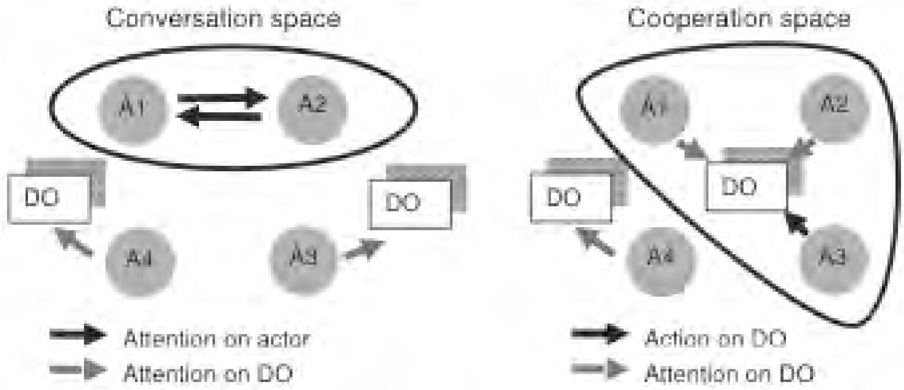
From this table, one can deduce that (refer also to figure 2):

- There is no direct attention on other designers
- Therefore, the conversation space is not active. The cohesion in conversation is null.
- There is some attention on one Design Object
- The cooperation space is active for three actors look at the same object.
- There is some cohesion in cooperation (see later)\
- Object N° 7 plays a mediating role (2 actors at least look at it). It becomes an Intermediary Design Object with a translating role (one designer is drawing), but no representing role (no "pointing").

3.5.4. "Activation" of the collective spaces.

In the definition of our concepts, the conversation and cooperation spaces are considered only when they are active, that is when two designers at least look at each other (conversation) or on the same Design Object (cooperation). Different configurations can be observed. Two are shown in figure 3, corresponding to the instants A and B (table 1 and 2).

For instant A (figure 3 a), there is a peer to peer communication, the others actors are like "witnesses" of this conversation (they can "testify" that the conversation occurred, but probably did not record it). For instant B (figure 3b), There is cooperation onto a DIO with three designers. For none of these instants, the cohesion is complete. This led us to define cohesion indices.



3 a) Instant A   3 b) Instant B

Figure 3. *Two configurations for instants A and B*

3.5.5. Cohesion indices

For better observing the difference between working in conversation and in cooperation, we defined two indices for each given period. This analysis is necessary since the activity needs indicators, allowing its graphic description as well as the comparison between experiments. To quantify this difference, we distinguished the configurations of the group of actors, according to whether they are looking at each others and discussing, or whether they look at the objects and discuss around them. We thus defined two quantitative indices for the cohesion of the individuals, taking into account the number of actors implied.

When an interaction implies the totality of the actors - 4 actors here - the cohesion of the group is high. Interactions with 3 or 2 people show a lower cohesion, even if, strictly, it would be necessary to be informed on the auditive and nonvisual attention of the various actors. The cohesion is thought to be penalised not only because one person (or two) will have to spend time to connect back to the group, but also because he will need explanations from his colleagues. We applied weights: 1 for four actors, 0.5625 for three actors, and 0.25 for two actors (0.5625 = 0.75*0.75; 0.25 = 0.5*0.5). These weights are the cohesion indices for each period. Thus, for instant A, the cohesion in conversation is 0.25; the cohesion in cooperation is 0. For instant B, the cohesion in conversation is 0; the cohesion in cooperation is 0.5625.

To appreciate the evolution of cohesion along time, it became necessary to "filter the signal". In a first investigation, we cut out each experiment in 5 minutes periods and made calculations of averaged cohesion indices. The indices are thus weighted according to the type of configurations and their occurrences during the 5 minutes period. This calculus is illustrated for a shorter period in table 3.

TABLE 3. Calculus of averaged cohesion indices, illustration.

Moment	Nb of designers in conversation	Conversation indice	Nb of designers in cooperation	Cooperation indice
00 :06 :38	0	0	4	1
00 :06 :49	0	0	3	0.5625
00 :06 :53	0	0	3	0.5625
00 :06 :59	0	0	3	0.5625
00 : 07 :01	0	0	2	0.25
00 :07 :04	3	0.5625		0
00 :07 :07	3	0.5625		0
Average		**0.16**		**0.42**

Conversation and cooperation are not strictly complementary activities. Designing is not only the combination / alternation of periods of conversation and cooperation, but also of individual work and works with few designers (For instance, here, a configuration with 2 + 2 designers is possible). Our definition of the two indices allows for the following distinctions:

- Cooperation versus conversation.
- Full cooperation versus partial cooperation
- Full conversation versus partial conversation

For instance, a limit but observed configuration can occur when the four designers work individually. In this case, both indices are null.

4 Examples of results.

We present here three graphs, but with few discussion (Pena 2005). The first one - figure 4 - is a quantification of the FBS model. To obtain it, the process of asking questions on concepts was not necessary: The FBS model has already been developed by J S Gero (2002), and the only rough data necessary is the coding of the verbal exchanges. Compared to design acts, it is easier to code according to a FBS classification. The results themselves surprised us because the three experiences we analysed showed quasi identical graphs even if the temporal evolution of F, Be, Bs, and S is different from one experience to another (For one experience, we had problems with the audio recorder. The internal microphone of the video cameras allowed us to observe who was speaking, but not to understand clearly the content of the verbal exchanges). The low proportion of F statements of the protocol can be explained by the nature of the design problem. Dotted lines are processes not present in the FBS model (Gero 2002), but observed. FS, BsS, and FBs are discussed in the thesis.

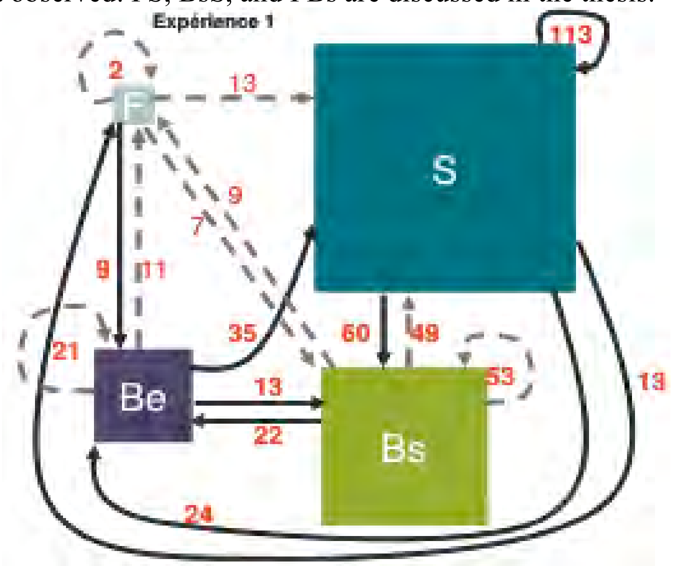


Figure 4. Quantification of Function, Structure and Behaviours and their links in the discourse of designers, experience 1

The second graph - figure 5 - shows the two averaged cohesion quantifications (averaged for periods of 5 minutes) in cooperation and in conversation. In particular, three periods show a higher proportion of conversation, corresponding to lesser utilisations of design objects.

The third graph - figure 6 – shows quantifications of translation and representation functions of the design objects (averaged, as for conversation and cooperation indices). When translation is important, this signifies that design objects are created or modified by more than one designer - in the collective space. There are periods where no "translation" is observed: design objects are not modified, or modified in a private way. An important "representation" is certainly associated with explanations and discussions around previously produced design objects.

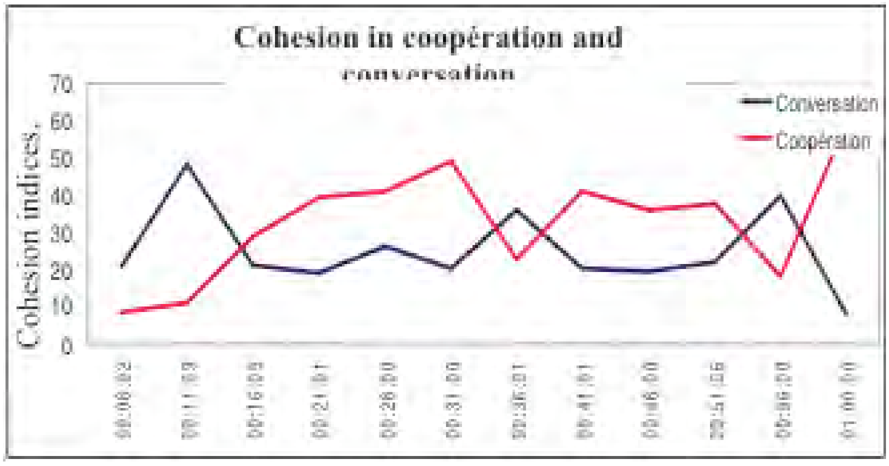


Figure 5. Average cohesion in conversation and cooperation, Observing period = 5 minutes, experience 2

5 Discussion and conclusion

Experimental laboratory observation has its drawbacks and advantages. The latter are the possibility to control - to some extend – the input parameters, to have a focused process, and to reproduce the experiments - a way to test the robustness of the analysing tools and research process. It allows also observing differences in designer's behaviours. The definition of the experiments is a central issue not sufficiently addressed (Dorst 1996). It must be preceded by a first building of concepts and models, and lead to rich and diverse analyses.

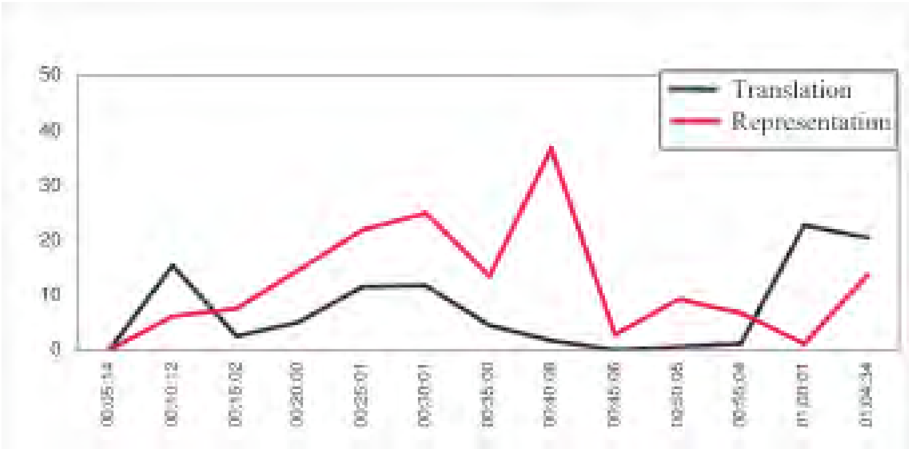


Figure 6. Translation and representation functions of all the design objects. Observing period = 5 minutes, experience 4

The beginning of a design research project is important: the researcher must define the issues, question the concepts and the bibliography to position his work, eventually build a first prototype of a model, design and test the experiments…In comparison, the time of the experiment is short and often gives the research process some irreversibility due to both the investment (the time of the Phd student) and the fact that the need for making other experiences is often felt later, during and after the analyses. The analysis of such experiments is long, and (from our experience) leads to the emergence or the transformation of concepts, models…

The proposed web of relations between data is a representation evolving during the research process. Its main function is to help for discussion. If it can help for the building of an experiment, its main use is for a constant questioning of the definitions of the entities in order to avoid possible confusions of terms - "As design emerges as a discipline, it needs to define and agree on basic terms" (Poggenpohl, Chayutsahakij and Jeamsinkul 2004), see also Love (2000).

Our work is neither deductive – for hypotheses and concepts often emerge or are reviewed when analysing a past situation– nor inductive – for laboratory experiments are designed to meet a research goal. A large amount of time is spend before making the experiments to define a reference model (which will be amended later), and to imagine the experiments (purpose, subject, allowed time, number of designers, roles… and the way to observe them). In this sense we work as designers: our goals, analysing tools, models, experiments … are the emerging features of a mostly cyclic process, which has to be designed at the same time as research means and results.

As other theses, Ezio Pena's one did not follow a linear path, nor an "analysis / synthesis / modelisation (test) / evaluation" process as suggested by the DRM. For instance, a first definition of remote experiences appeared too difficult and has been abandoned. After the experimentation, many graphs showing the evolution of rough data have been made with very few results. Due also to a lack of tools adapted to these experiences, we had the impression that a work was necessary for structuring and analysing the data, and effectively means for analysis have been constructed for obtaining results: the research tools are also a result of the research process. Later, we felt the necessity to "give sense" to some data by defining new concepts (and using concepts defined by colleagues). The web of data shown here is itself a product finalized during and after the writing of the theses document. Being unable to reproduce a past experience, we simply wonder whether an earlier construction of such a graph could have helped us. Our feeling and positive (but nuanced) feedbacks from some PhD students and colleagues with which we discussed the initial research cycle (Prudhomme Brissaud & Choulier 2005), allow us to give a positive answer.

To follow Friedman "Research is a way of asking questions" (Friedman 2003). The proposed representation of a web of data relations can be used as an aid for structuring research questions and imagining ways to define concepts. It is of course relevant only when data complexity has to be managed. As practitioners, we need representations to engage a reflexive conversation (a known reference).

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CONTENT-BASED DESIGN ANALYSIS

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Abstract. Content-based design analysis investigates design phenomena as processing mental contents and explains the phenomena on the grounds of involved mental contents. In this paper we show why and how the content-based design analysis is applicable in studying the core phenomena of engineering design, namely the thought processes of individual engineers. In this paper, we will apply content-based analysis to shed light on the nature of thinking and creativity in a large scale industrial design process. We suggest that it is not divergent in the sense that people would produce floating ideas. On the contrary it is very focussed on the defined key problems, and progress is made by solving these problems. This kind of industrial design process can be called convergent.

1. Introduction

Engineering design is a very challenging area for multidisciplinary analysis. It is a process in which most important new things are created in industry. The most important technological breakthroughs have always been the outcome of creative design. However, it is also a source of severe errors in the economic process. Minor mistakes may have serious consequences, even though everything had otherwise been correctly taken into account (Perrow 1999). For these reasons it is understandable that design processes are intensively analysed in modern science.

Design is a complex industrial activity and therefore it can justifiably be considered from very different points of view. It is common that researchers with substantial experience in industrial engineering design collect their own experiences to form design theories (e.g., Ehrlenspiel 2003, Lindemann 2005, Norman Cubbitt, Urry and Whittaker 2000, Pahl and Beitz 1986, Pahl et al. 2003, Ullman 2003, Ulrich and Eppinger 2000). This approach has undoubtedly been the most successful way of investigating design processes. It has made possible to generate rational descriptions of good design processes. It has also created systems of normative design approaches to eliminate risks, which can emerge either in the form of design errors or loss of time and rising costs. It has created systems for best practices and has provided important knowledge management systems, design languages or CAD/CAM type design tools. Practice has demonstrated that real progress has been made in this sector.

Design produces plans for realization. If we think about a giant construction such as a paper machine, which is in the focus of our interest, we may assess just as a theoretical thought experiment that there are for example 50 000 different kinds of parts. Designing any individual part from the first idea to an industrial level of quality has required many ideas and refinements of those ideas, say, on average a thousand ideas or transformations of mental representations. Thus, designing just the components of a paper machine can be estimated entailing tens of millions of design ideas.

From our point of view, the essence of industrial design is human thinking, which takes place both in the individual mind and among the groups of designers. Therefore, we should approach design as human thinking and apply in its multidisciplinary analysis concepts and methods typical for the psychology of skilled thinking. However, to be able to find the most efficient way to apply the psychology of thinking to the analysis of design processes, it has been necessary to develop the theoretical grounds of the current psychology of thinking. This approach can be called content-oriented or content-based psychology (Saariluoma 1990, 2002, 2003).

All design ideas or thoughts have information content, if not, they are not design ideas and no one could produce anything by following them. Thus, information content is a necessary condition for something being a design plan. Naturally, designing is the creative activity which produces the information content of the plans. The essence of this thought process is production of mental contents embodied in the actual plan (Saariluoma 1995, 2001, 2005, Saariluoma & Maarttola 2001, 2003).

These intuitions lead to one key principle. If we investigate human thinking, it is necessary to investigate it as a process of mental contents. Indeed, one can argue that human behavior is controlled by the information contents of human mental representations. The information contents of these representations are transformed when people think and the success and failure of a design process depends on the adequacy of the mental contents of the designers. This is why it is logical to assume that by investigating mental content there are numerous phenomena relevant in design thinking, which can be explained on the grounds of mental contents in the mind of an individual designer. For those reasons mental content is taken as the main explanatory ground in our approach and it can be called content-based psychology of thinking.

Human thinking is about mental contents. This is a very clear intuition, but there are numerous alternative ways of building the system of theoretical concepts (Allport 1980a, 1980b, Fodor 1990). A typical example has also been schema-theory and other related theories (Bartlett 1932, Piaget 1952, Neisser 1976, Selz 1913, 1922). In these systems, the generalizations have often been achieved by abstracting the actual contents. The traditions speak mainly about schemas, but not of their actual content. In the present approach, contents are discussed as contents, because it is an explanatory category (e.g. Saariluoma 1990, 1995, 2002). This means that the contents of some particular mental representation logically explain some particular behavioral phenomenon. Generalizations are based on content-types such as functional reasons, which express why a representation has some particular content element, or thought models, which characterize complex content elements in thinking (Saariluoma 1990, 1997, 2005, Saariluoma and Maarttola 2003).

A concrete example of a functional reason could be that we *use the nip in the press unit of a paper machine for drying the wet paper web.* The contents of this functional principle can, on its part, be used to explain the economy of the ENP-problem solving engineers' way of thinking, because functional reasons generally explain the economy of human thinking (Saariluoma 1995, Saariluoma & Maarttola 2003). This means, how it is possible for human beings to concentrate on the essential aspects of the problems instead of the mindless searching through the endless jungles of alternatives.

An example of a thought model could be induction error: *We have always done it in this manner, and therefore we can also use this solution here* (Saariluoma 2002). The latter model is risky, but we can find it in the structure of economic thought examples and use them to explain some incorrect economic thought processes (Saariluoma 2002). Both types of examples illustrate what is meant by explaining the content-based approach.

Content-based analysis of thinking has lead to some paradoxical insights. The most important so far has presumably been the difference between perception and apperception. If we look at the contents of human mental representations it is possible to notice that they very often entail non-perceivable content elements such as infinity, friction, possible, tomorrow, foreign trade or constitution. These content elements are non-perceivable kinds and therefore it is logical to assume that the contents of mental representations are constructed by apperception rather than stimulus-bound perception. This difference is naturally important for the analysis of design thinking as it so often relies on non-perceivable kinds such as mathematical principles or non-perceivable particles.

On this ground, we think that it is justified to investigate designers' thinking as creation, generation, modification and working with mental contents. We call this approach content-based design analysis. Its core idea is in investigating design phenomena as processing mental contents and explaining the phenomena on the grounds of involved mental contents (Saariluoma 2005, Saariluoma and Maarttola 2001, 2003).

Our way of looking at this differs from many other approaches to engineering design for its psychological orientation. Traditionally, engineering design has been an art of applying the so called engineering sciences in solving up-coming problems (e.g. Kesselring 1954, Shigley & Mitchell 1960/1990). From the beginning of 1960's various systematic design engineering methods were introduced, mostly for the purpose of training new designers more effectively, but also for promoting the engineering design practice (e.g. Asimow 1962, Rodenacker 1970, Claussen 1973, Roth 1982, VDI 2221, VDI 2222, VDI 2225, Hubka & Eder 1984, 2001, Pahl & Beitz 1986, Pahl et al. 2003, Ulrich & Eppinger 2000). In most cases these approaches have not given much interest to design as a human psychological activity. More recently attention has been paid to the psychology of design (Akin 1980, Pahl et al. 1999, Kavakli & Gero 2003, Tversky 2003, Visser 2003, Ulman 2003). Our approach differs and contributes their efforts in calling attention to the mental contents of the designers' way of thinking.

In this paper, we explicate and define some of the major characteristics of our approach. In order to get full clarity of the program, we consider the nature of content processes on individual, organizational and industrial field levels. The reason for this approach is that in real-life design the representations with information content are produced simultaneously and somewhat chaotically on each of these levels.

2. Reconstructive method

The goal of our work is to understand, how designers think during a large scale industrial design process, which has lasted over two decades. In concrete, we investigate the development process of the concept of the extended nip press (ENP) in Valmet/Metso Corporation from 1983-2003. This kind of industrial process may take decades. Therefore, one cannot apply any kind of experimental methodology when analyzing thought processes during the long ranging processes. The only possibility is to reconstruct what has happened.

In our case, we started the reconstruction by arranging four separate group interview meetings in spring 2003. Altogether 12 engineers, former and present employees of Valmet/Metso Paper Inc. attended these meetings and discussions. At the beginning of June 2003 we started the focused individual interviews with five key engineers, who had participated in the development process of the extended nip press. Representative set of concurrent documentation was collected and analyzed. By means of repetitive interviews the picture of the design process was gradually developed. We call this method reconstructive analysis.

Content-based reconstructive design analysis intrinsically requires that the researchers are able to learn to understand *the actual content* of the design process. This fact entails some prerequisites of the research process. It does not mean that the researcher must be necessarily an expert in the domain, but it does mean that the researcher must have the ability to learn to understand the specific domain professional knowledge. Content-based analysis is definitely different from those approaches which analyze design *on a general level*; searching for such properties of design thinking that can be applied in analyzing thought processes emerging in any kind of design process. We do not deny the importance of the high level design studies. They certainly give rigor to the explication of the design process. Our purpose is, however, to point out the importance of the inbuilt logic of the reasons, which lead to the particular results of engineering design.

Naturally, it is impossible to explicate all the details in such process as the ENP design. Therefore, the key challenge is to find the essential aspects of the process. This means such aspects which can give relevant information about the design processes. How much one such example can give us is always limited, but there is no other way to penetrate into the real world design process but to analyze and compare reconstructed cases. In this way we gradually learn more about the complexity of design thinking.

3. Dynamics between the levels of design

Content-based design analysis is empirical investigation into the construction of a plan. On an industrial scale the total plan is built up by the resources of the commercially driven organization. However, this process always pre-supposes individual human thinking. All ideas are produced by an individual designer. This is why the content-based principles of an individual designer’s way of thinking form the core challenge for content-based design analysis.

In our investigation some aspects of an individual designer’s thinking have been found. One major problem is the economy of designers thinking. People do not mindlessly search combinatorial possibilities. Their thinking is focused and economical. On the grounds of content-based analysis, we have suggested that economy of designers thinking can be explained in part by its functional organizational goals. Here we have called attention, for example, to the role of strategic decisions in the generation and formulation of the knowledge representations of individual engineers.

Example 1: As an example of the interplay between the above mentioned levels of design activities let us consider the starting situation of our case in the early 1980's. According to our empirical material[1] the demand for an increase in the production speed of paper machines in the late 1970's was a major functional reason for restructuring the traditional ideas about the operating units of the paper machine.

One basic problem was that increasing the speed would consequently decrease the time for water removal. This caused the need for increasing the time for a sufficient press impulse (pressure) x (time). Quotation from the interviews (T10: 00,09,50)[2]:

...on the other hand, at that time the speed [of paper machine] was increased... Actually, when joining Valmet at 1979 the task was to run a project for increasing the speed. There was discussion about so called "closed run" [of the paper web] in the press section... The idea came actually outside of Valmet... It guided actually to the road of increasing the speed... There were apparent problems in raising the speed... Supporting the paper web was one solution... Then we saw at the same time that when increasing the speed the dry content goes down... So, lengthening the pressing time was a natural solution... and it was apparent that putting press nip after another would be rather expensive solution... So, if there would be a possibility to take care of the matter by extending the nip... so why not.

Explanation: This quotation clearly reveals how the initial situation of our empirical case and the content of thinking of this particular engineer were determined by the necessary business strategies of the time. In order to understand the quotation it is necessary to understand the non-explicated content of these words. These hidden aspects can be traced by comparing the statements of the interviews with the common knowledge of the domain and with the relevant documentary material, as was stated above and will be further developed in Nevala (in press).

We have used for example relevant contemporary papers from professional magazines like Wahlström (1960, 1979), Paulapuro & Nordman (1991), and comprehensive modern handbooks and other learning material like Gullichsen & Paulapuro (1998-2000), KnowPap (2005), and the biennial publications of Valmet/Metso Technology Days (1995 – 2003), just to mention a few central sources.

Obviously the competition and demand from the markets necessitated the strategic decision of increasing the running speed of paper machines. This

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[1] These example cases are excerpts from the empirical material of our investigation, which includes over 17 hours of interviews, relevant documents and nearly hundred patent publications.

[2] Position of the quotation on the interview recordings CD: Track 10, 00h 09min 50sec.

decision determined the contents of the resulting paper machine development process. The thought process of this engineer readily acquired the content elements of the initial situation. His apperceived representation included personal intuitions and knowledge as well as general technical information about the press section. This initial representation was a self-consistent, logical combination of all elements (comprehended by this particular engineer) of an industrial quality product of the time: the press section of Valmet paper machine (Fig. 1).

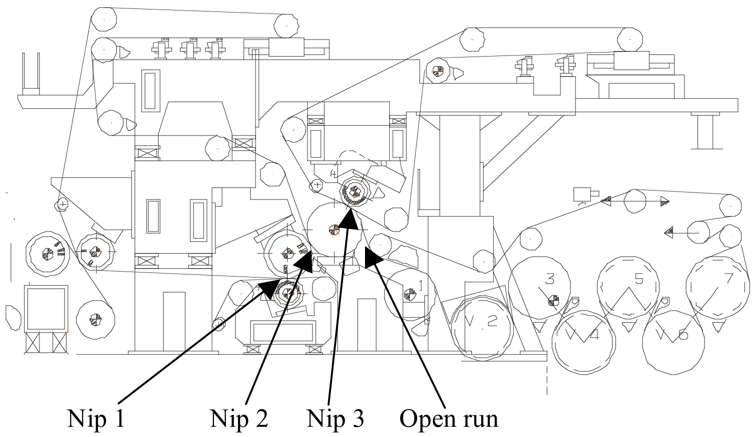


Figure 1. Valmet SymPress II, 1983.

However, alteration of one design parameter caused inconsistencies in the representation: if the running speed was increased the pressing time in the existing three nips decreases and consequently water removal from the paper web would become insufficient. Furthermore, difficulties in the open run sections, where the paper web is not supported by a felt, could be expected.

These inconsistencies focussed on the problem contents and triggered a restructuring of the representations of all the engineers and executives who were responsible for the competitiveness of the press section of Valmet paper machines. A typical reflective process for design engineering thinking was initiated. The quotation states that this process was already going on when this particular engineer got his assignment. Consequently, he readily acquired into his representation the prerequisites of the initial situation, that is to say, the content elements like the prevailing structure and process knowledge of the Valmet press section, the inconsistencies of it in regards to the required speed increase, the previously discussed ideas for resolving the expected problems, etc. Also typical for this kind of globally shared development request was that the reflective process was performed with collaborating partners.

It is interesting to pay attention to the mechanisms of creativity. The markets and other external circumstances give requirements for the designers. The development of ideas focus on certain well structured sub-problems. Finding these problems is part of the creative process. So, the economic impossibility led to the rejection of multiple nip solutions and lead to restructuring. Consequently, the idea of an extended nip became the focus. There is no sign of freely floating ideation, but on the contrary the crucial breakthroughs are made by restructuring very well focussed problems. Concentration, focussing and pointed restructuring are thus the major characteristics of creativity.

Focusing on the essential content elements of the development process: As stated in the quotation above, the essential content of the development process (already 1979) was to find solutions for overcoming the difficulties arising from the increased running speed of paper machines. Apparently, the first focus area was to support the paper web all the way through to the press section; the so called closed run. Tests showed that the paper web started to flutter in sections where it was not supported by the felt or other fabrics. The second major area was composed of the ideas of lengthening the press impulse. A management level project for improving the press section; the Press 1983 project was launched. Also a program of press simulation tests was carried out. Eventually, the idea of supporting the paper web led to the OptiPress concept, but it was not developed until the 1990's in parallel with the development of the SymBelt concept (Fig. 3). A more detailed reconstruction of the progression of these domain specific content elements will be presented elsewhere (Nevala in press).

Here we discuss a little more about one potential solution for the problem of the decreasing water removal in faster machines, which is mentioned in the end of above quotation, namely the previously known idea of an extended press zone (see for example patent publications; Canada 1948; USA 1966; Germany 1972; USA 1974; Canada 1975). A leading paper and board machine manufacturer of 1970's and 1980's, the Beloit Corporation, was the first to introduce during 1981 in the USA a shoe press, where the wet web was pressed between a fixed roll and a flexible belt by a concave beam, which was called the "press shoe" (Figure 2).

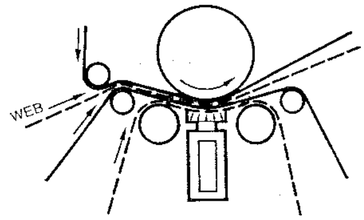


Figure 2. Extended nip press (Justus and Cronin 1982).

All other manufacturers were obliged to make strategic decisions in order to meet this challenge on the global markets. The idea of an extended nip zone was actually a self-consistent solution for the problem, but there were several obvious machine technical, material technical, legal (e.g. an extensive patent "jungle") and economical problems confusing the decision situation.

To make a long story short, the content-based inferences and strategic decisions after all these individual and organizational efforts concluded that there was not enough evidence in applying for this technology in paper machines. In board grades the construction could perhaps be cost-effective. Valmet only produced paper machines at the time. The idea was abandoned.

However, corporate level business decisions changed the situation almost concurrently. Board making machines were included into the product assortment. Figure 3 illustrates the chain of strategic decisions and the steps for improvements on the SymBelt-concept according to our empirical material

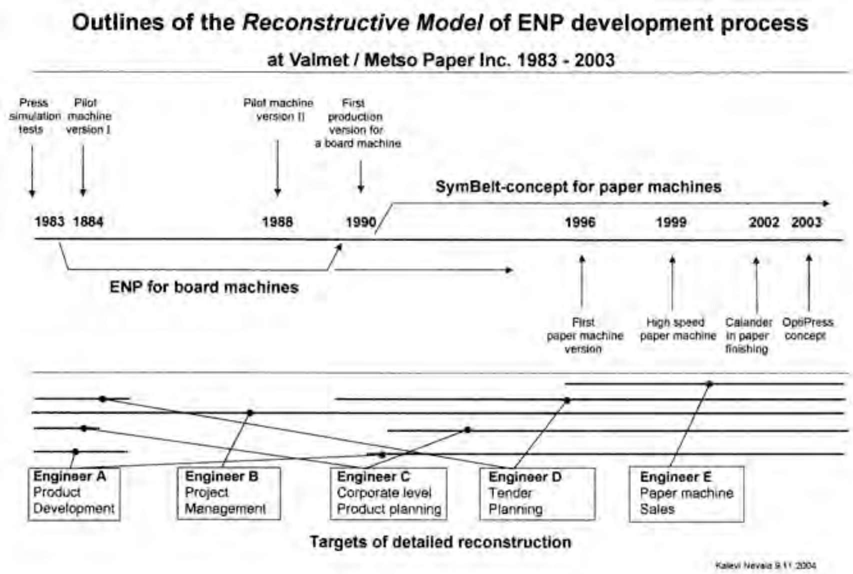
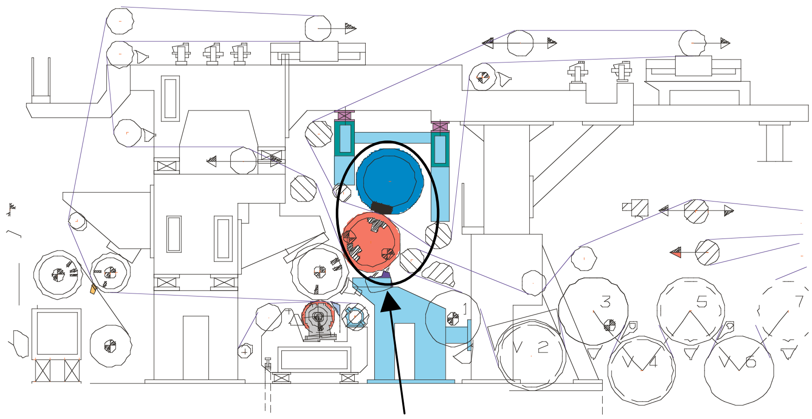


Figure 3. Outlines of the case of our content-based design analysis.

Here, the organization first rejected the possibility of the ENP development for paper machines. The organizational management did not believe that the technology could be applied to thin paper grades such as newsprint paper cost-effectively. This interpretation of the critical content elements of the development process led to a strategic decision, which meant a delay of several years. In fact, it could have prevented the development for a longer period, unless it had been necessary to develop the technology for board making machines.

Eventually, the combination of organizational decisions and individual thought processes outlined in Figure 3 led to the new concept of the SymBelt press, in which the ENP was also utilized for paper machines; in the so called SymPress B concept (Fig. 4) and later on also in the OptiPress.

This example demonstrates how the individual, organizational and global levels of design are intertwined: there are globally shared content elements and company level business requirements which determine to a large degree the actual contents of individual design engineering thinking. It is quite natural and practical to investigate the interplay of this complex totality by the content-based approach.



SymBelt concept

Figure 4. Metso SymPress B, 2003.

In this long analysis, we can again see how concentrated and focused restructuring forms the core of the creative process. We can also see, how focused creativity can be found on all organizational levels and how the decisions on the different levels from marketing and strategy to actual machine design play somewhat chaotic "interaction games", in which one decision may stimulate or inhibit some other processes. Nevertheless, the focusing of problem solving processes is very explicit.

Example 2: Another example concerns the development and restructuring of ideas in patents, which is one of the major enigmas in any field of industry. In reconstructive research, it is naturally good to have several examples. When investigating history, it is not necessarily possible to look for additional examples, but in reconstructing engineering thought processes it is often possible to find additional cases within one single design process.

Therefore, the reconstructive analysis of engineering design is half-idiographic.

At the beginning of the 1980's at Valmet Paper Machines several projects were initiated. The product development and design engineers were encouraged to produce ideas to achieve new and better inventions where the above mentioned problems, caused by the speed increase, would be solved. Our empirical material illustrates that this kind of thinking was actually the core of the innovative activities at Valmet Paper Machines at that time.

(T1: 00,01,38): *...It was the good old strategy of being the best second… Nothing moved in the organization if the competitor had not done it before… Customers did not ask for it… There could be in principle a superior product… but there were no demand for it…*

(T7: 00,00,30): *...And if it seems to be new… and I know the existing patents well… then the goal maybe to make a new invention…*

Figure 5 illustrates how this kind of restructuring process advanced in practice. The Beloit Corporation managed to gain patent protection for a simple idea of supporting the press shoe by a single joint in such a position that the shoe acts as a hydrodynamic bearing.

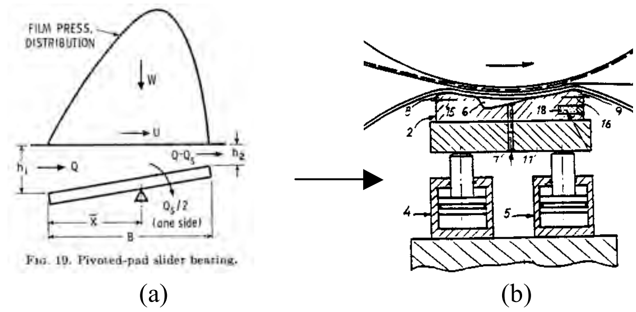


Figure 5. Result of the intentional restructuring mode of thinking of a designing engineer, i.e. a virtual joint, constructed by two load cylinders (b) instead of one mechanical joint (a).

Thus, the simplest idea could not be used by Valmet. Consequently, the patent protection was bypassed through accomplishing the hydrodynamic bearing with two load cylinders. This restructuring of the construction also created additional beneficial content elements to the mental representations of the participating engineers, e.g. the possibility to adjust the press curve and the tilt of the press shoe.

This example provides us with information about focusing and restructuring. This is the nature of restructuring. The designer has the previous solution at his desk. He sees in it some presuppositions, i.e., how the problem was earlier solved on a technical level. The actual restructuring meant breaking up the earlier idea that the particular solution was the best possible. In this example the earlier very simple technical idea was a straightforward application of the well-known principle of hydrodynamic bearing, but, as the idea was patented for use in the press units of paper machines, the designer was obliged to restructure his representation of the "press shoe" construction. The restructuring process included analyzing the key properties of the earlier solution and building up reflective ideas for a new invention, which should include all necessary functional properties, but must also be very different from the earlier ideas so that it can be patented. The resulting technical solution with two rows of cylinders opened totally new aspects: the conditions of the hydrodynamic bearing could be adjusted, which is not possible in the former construction. This means that restructuring rebuilds the earlier system of presuppositions and replaces it with new ones (Saariluoma 1997).

4. Conclusions

Our examples provide us with some milestones in a long process. The feature we have paid attention to is the nature of creativity. Quite often creativity in engineering design is seen as a divergent process, like in Brainstorming and other methods in which free association have been of importance (e.g. Gordon 1961, Prince 1970, Osborn 1979, Altshuller 1999). However, if we think of such objects as a paper machine with its millions of embedded ideas, it is necessary to see that freely floating associations do not necessarily lead anywhere. The true creativity in our example is much more disciplined. The core of creativity is to concentrate on the most relevant contents and solve the problems they pose to designers.

This kind of creativity can be called convergent. It is characterized by concentrating on core contents. External requirements such as changes in marketing or technological knowledge make some aspect of the huge product core areas. They are areas, which make it possible to make real progress. The metal contents entail contradictory requirements, which must be solved. Thus convergent creativity is characterized by focusing on the core contents and restructuring these contents, i.e. finding the right arrangement of cylinders. It is important to emphasize that restructuring is focused and it replaces one content with another. From our point of view, understanding the nature of convergent creativity is one of the key challenges for content-based analysis of creative thinking in design.

After the example provided by the analysis of creative thinking, it is logical to reflect the nature of the approach. Content-based analysis concentrates on working with all aspects of mental contents involved in design. Its basic method is explication. This means that the phenomenon under research is separated in the total flow of design thinking. Thereafter it is defined, its major properties are clarified and it is named for further discussion in the scientific community. In this way, any content-relevant phenomenon can be submitted under investigation. Naturally, this process is highly qualitative, though there are no obstacles in using quantitative argumentation. The point of view depends on the research problem. The qualitative emphasis is natural as human thinking is a content-based process. Its core is in the information content of the thoughts.

The investigation to design processes can take many different forms. It can be carried out by laboratory tasks, but it may also entail interviews, ethnographic techniques and extensive documentary analysis. Often the latter, the way of working provides the best methods of working with large industrial design processes with hundreds of collaborating designers.

In the present case, we have added to the explication reconstructive analysis. This is a natural way of investigating very large scale design processes. There are many methodological problems in investigating the way mental contents are processed in such a process. However, there are not too many alternatives for investigating real life industrial design.

One may naturally ask what the information is like we get from design by means of the content-based approach. Is it ideographic or nomothetic? Should it provide general laws or what should the general laws be like, when we work with mental contents? The answer to these questions is straightforward. There is no difference in the meta-science of content-based analysis compared to such alternative approaches as cognitive capacity based argumentation (Saariluoma 1997). The ultimate goal is to find a rational understanding of the phenomena of design.

In practice, in content-based design analysis, it is important to find mechanisms which integrate various types of contents, which explains why some ideas make sense, what are the tacit presuppositions and what kind of knowledge is required. The goal is qualitative description of thinking in design and in this process it is naturally important what is thought and why it makes sense. This is why it may shed new light in our understanding of industrial creativity.

The problem of generalizations can be solved in two ways. Firstly, one may look for generalizations through abstraction. One can look for types of content, which can be found in numerous environments and build general principles on their properties. Functional reasons may serve as an example (Saariluoma 1990, Saariluoma and Maarttola 2003). The other way is more methodological. One may look for concepts and procedures, which help us to understand very different types of domains and problems (Saariluoma 1995).

A crucial point in engineering thinking is to understand the functions, uses, significances or meaning content of the considered visible object. Interestingly, Wittgenstein (1958, remark 12), for example, calls attention to the similarity of engineering understanding of the uses of objects and uses of words. It is perhaps good to remind ourselves of his points though our conception is essentially different with respect to mental representations and some other things. Wittgenstein seems to assume that one must have a clear idea about the regularities which govern the engineering structure (Cf. Wittgenstein 1958, remarks 466-475). One must understand the web of grounds in making the object such as a boiler safe. One must see the objects as something. One must find the correct aspects of the perceivable objects. One must understand the essential and be able to restructure this web of pre-conditions. In our terms this means that researchers must be able to penetrate into the information content of designers' mental representations to be able to understand the design process itself.

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ENTROPY MEASUREMENT OF LINKOGRAPHY IN PROTOCOL STUDIES OF DESIGNING

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Abstract. This paper explores the use of information theory to measure linkography in protocol studies of designing. It outlines the ideas behind using Shannon's entropy as a measure of opportunities for idea development in team designing. The entropy measurement can be used to assess a whole design session or it can be used to evaluate the progress of a session by taking incremental measurements. Two cases are used to illustrate this method. The paper concludes that this method is able to assign signatures to design sessions that characterize the opportunities for idea development.

1. Protocol Studies in Designing

According to Akin (1998) the first formal protocol analysis that study designing was conducted by Charles Eastman (1969). Eastman's study contributed to the current understanding of what architects do when they design in the form of a information process model. Eastman's view had been challenged by Schon and Wiggins (1992) which suggested designing as a reflective conversation with material, that the basic structure of information flow is interactive. Cross (2001) gave a summary of design cognition from the results of interdisciplinary protocol and other empirical studies of design activity in the past thirty year and asserted that protocol analysis has become the most likely method to study cognitive activities of designers. Dorst and Dijkhuis (1995) suggested there were two types of protocol studies namely process- and content- oriented protocol analysis to capture the two different paradigms mention above. Linkography was first introduced to protocol analysis by Goldschmidt (1990) to assess design productivity of designers where she suggested linkograph acts as a bridge between the design process and the design product for assessment (Goldschmidt 1992). In a way this method bridged the process and content oriented protocol analysis of designing. The following section gives a summary of linkography relevant to this paper, readers should refer to Goldschmidt (1990, 1992) for further details of this method.

2. Linkography

In this technique the design process is decomposed by parsing the recorded design protocol into small units called design moves. Goldschmidt defines a design move as: “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), or “an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed” (Goldschmidt 1992). A linkograph is then 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. Figure 1 is an example of linkograph from Goldschmidt (1992). The design process can then be looked at in terms of the patterns of the linkograph which displays the structural design reasoning.

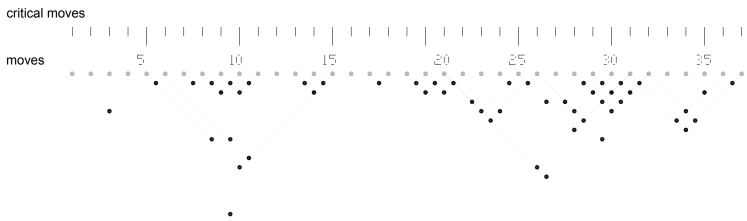


Figure 1. Linkograph from Goldschmidt (1992) with the position of critical moves indicated by “v”.

Goldschmidt identified two types of links: backlinks and forelinks. Backlinks are links of moves that connect to previous moves and forelinks are links of moves that connect to subsequent moves. Conceptually they are very different: “backlinks record the path that led to a move’s generation, while forelinks bear evidence to its contribution to the production of further moves” (Goldschmidt 1995).

We consider design moves as the externalization of the mental processes. The collective moves can be seen as the clustering of interaction among ideas. The progress of a design session can be observed through the analysis of the linkography. With an understanding of the construction of a linkograph, one is able to comment on the design behaviour without studying the design protocol. Goldschmidt (1992) suggested that the linkograph pattern of a productive designer will be different from that of a less productive designer. Productive designers will elicit moves that have a high potential for connectivity to other moves, while less productive designers will have more random trails with moves that did not had a high potential for contribution to the design concept (Goldschmidt 1992). Besides, designers start the design process by exploring different options and then select one to develop which will produce a very different linkograph compared to designers using a holistic approach without exploring different options. The interpretations of the linkograph lacks objectivity. We propose to use Shannon's entropy as a measure of the linkograph and we start the exploration with two case studies of team designing.

3. Case Studies

Two pilot cases were conducted to investigate the use of entropy as a measure of the design session. Case data was obtained from the CRC for Construction Innovation project titled: Team Collaboration in High Bandwidth Virtual Environments. Both cases involved design teams collaborating over an architectural project with different conditions.

Case I was a in-situ design session carried out in a Sydney architectural office. Two architects, one more senior than other, were involved in the design of a commercial building in Canberra city centre. This design session occurred after a review and planning session subsequent to a client meeting. In this session the designers revisited the relationship between vertical circulation and the void areas so as to satisfy the client's preference. The raw data was the video recording. Figure 2 is one image from this session and Figure 3 is the first sheet of drawing that they produced in this session, which will be analysed in this paper.

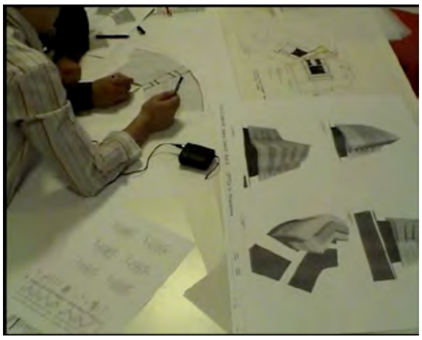


Figure 2. Face-to-face session, Senior Architect starts drawing the core and the bridges after 4 minutes.

3.1. QUALITATIVE ANALYSIS OF THE FACE-TO-FACE SESSION

During the first 10.5 minutes of the session, the designers frequently used drawing and gesturing to communicate without explicit verbalizing, and nearly all verbal protocols were accompanied by non-verbal actions; they referred to materials from previous designs; they drew different types of diagrams, sometimes separately; and they referred back and forth to the main plan drawing. Design actions were occurring in parallel, sometimes when the

Senior Architect was working on the large drawing the Architect would draw on another sheet of paper or retrieved older drawings. There were interruptions like setting up of the microphone for recording at the beginning and a phone call for about a minute towards the end. The leadership role was clear, the Senior Architect controlled and led the session. The designers were dealing more with the structural or formal aspect in this session – where things should be and how they related to each other so as to satisfy the client.

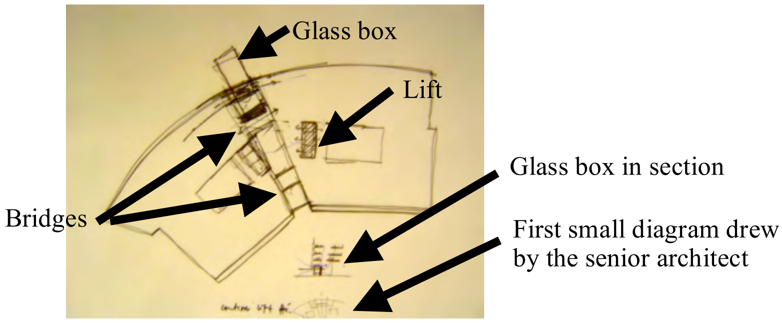


Figure 3. The first page of drawing the architects produced in the first 10.5 minutes with annotation added; this sheet was mostly drawn by the Senior Architect, the other Architect had a small diagram on another sheet.

Case II was a in-vitro session which simulated distant collaboration of two designers, an Architect and a Landscaper, with the use of computer-mediated tools. Tangible interfaces, Smartboard and Mimio, together with Microsoft NetMeeting were used in this experiment. NetMeeting contains a shared whiteboard and a video conferencing tool. The designers were asked to design an art gallery in a harbour front triangular site with level changes. Both their displays and actions were recorded as shown in Figure 4. Figure 5 is the first page that they produced which will be studied and compared in this paper; annotation is added to show the meaning of their drawing.

3.2. QUALITATIVE ANALYSIS OF THE NETMEETING SESSION

In this session the designers were given a new design task, so they were focusing more on the functional or conceptual aspect of the design with time spent on studying the brief. Figure 5 is the capture of the first page from the screen and the annotation was added by consulting the protocol. Overall we can observe that the Architect took the leadership role in this session and did most of the drawing. In the NetMeeting session interactions were more sequential and consisted of more affirmations compared to the face-to-face session and there was not much gesturing. There were more interactions among ideas, drawings, gestures, and verbal communications in the face-to-face session. A more detailed analysis of both sessions can be found in Kan and Gero (2005a).

Figure 4. Case II, NetMeeting session, the designers translating the issues into drawing in the beginning of the session

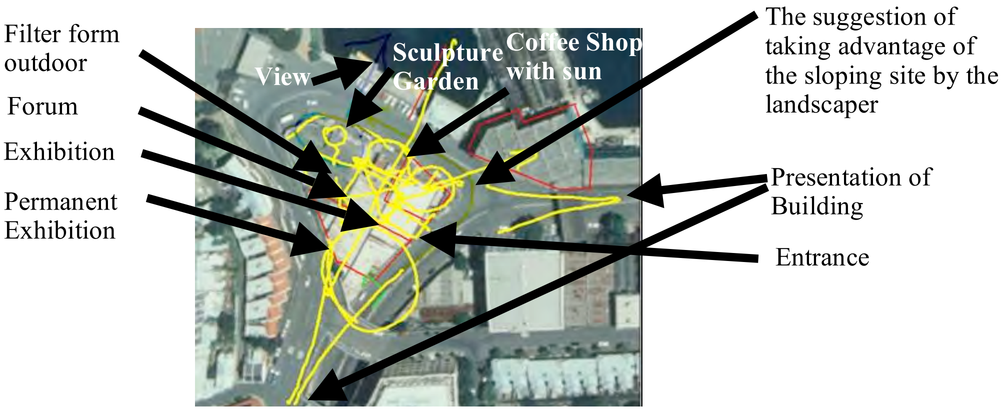


Figure 5. The first page of the NetMeeting session, mostly drawn by the Architect

3.1. LINKOGRAPHY OF THE TWO SESSIONS

There are 98 moves in the first 10.5 minutes with 299 links to produce the first page of drawing in the face-to-face session. In the NetMeeting sessions they took 6.5 minutes to produce the first page with 97 moves and 277 links. Figures 6 and 7 show the linkographs of the two sessions.

We can observe from the linkographs that in the face-to-face session links are more intense over the whole session where as in the NetMeeting session links are dense towards the end of the session. There is an obvious chunk, at the beginning of the NetMeeting session, but not in the face-to-face session. Overall the linkograph of the face-to-face session is more integrated but in the NetMeeting session there are sequential groups of moves.

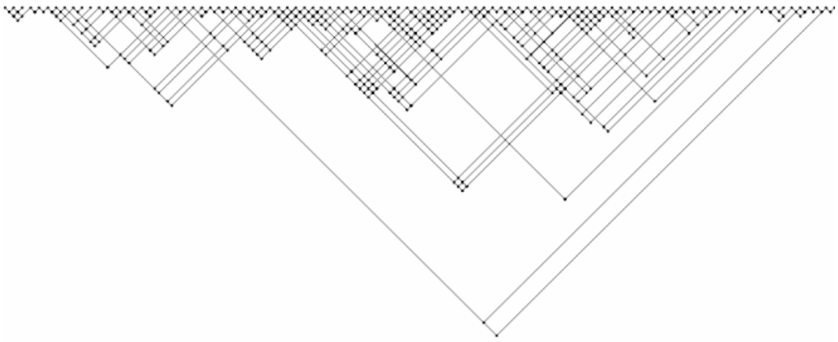


Figure 6. The linkograph of the first 10.5 minutes of the face-to-face session

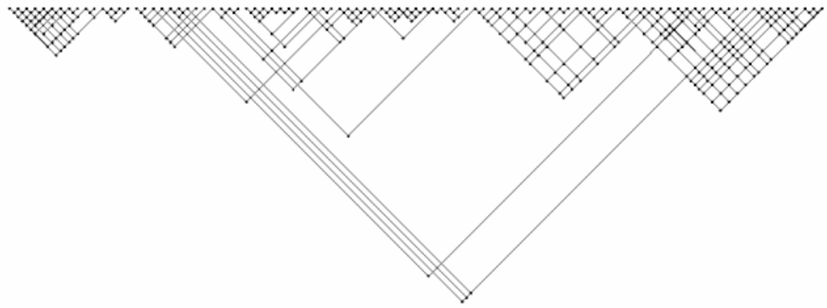


Figure 7. The linkograph of the first 6.5 minutes of NetMeeting session

4. Entropy Measurement and Interpretations

In Shannon's (1948) information theory, the amount of information carried by a message or symbol is based on the probability of its outcome. If there is only one possible outcome, then there is no additional information because the outcome is known. Information can then be defined related to the surprise it produces or the decrease in uncertainty. Given that event E1 has a lower probability than event E2, I should be more surprised if E1 had occurred, hence I get more information. The entropy H, the average information per symbol in a set of symbols with *a priori* probabilities, is

$$H = p1*h(p1) + p2*h(p2) + \ldots + pN*h(pN) \tag{1}$$

Where p_1, … p_N are probabilities corresponding to S_1, … S_N states and h(p) is the information-generating function devised by Shannon which equals $-\log_b(p)$.

$$\text{Therefore } H = -\sum_{i=1}^{n} p_i \log_b(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \tag{2}$$

In this study we measure entropy in rows of forelinks, backlinks, and horizontal links (horizonlinks) according to the ON/OFF of a link, Figure 8. Following Shannon's theory, formula (1), in each rows H becomes:

$$-p(\mathrm{ON})\mathrm{Log}(p(\mathrm{ON})) - p(\mathrm{OFF})\mathrm{Log}(p(\mathrm{OFF})) \quad \text{where } p(\mathrm{ON}) + p(\mathrm{OFF}) = 1 \quad (3)$$

The reason for measuring forelink and backlink entropy is because of their conceptual differences as described in the previous section. Here we introduce another link type called *horizonlink*. Horizonlink bears the notion of length of the links which is a measure of time (separation) between linked moves or we can view it as a measure of the distances of the linked moves. This reflects the cohesiveness of the session.

The maximum entropy (most random) of each row occurs when the ON/OFF of the links are most unpredictable, that is, half of the nodes in the row are linked and half of the nodes in the row are un-linked. Figure 9 plots the value of H against formula (3).

Figure 8. (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks.

The graph in Figure 9 is symmetrical, the slope of the graph decreases sharply as the probability moves away from 0 and 1. This indicates that when the links moves away from determinate values of 0 and 1 (all un-linked and all linked) the H value increases rapidly. In principle this is different from Goldschmidt's (1995) interpretation of productivity where more critical moves (moves with more than 7 links) and high value of link index, irrespective of the total number of possible link, are valued as more productive. Kan and Gero (2005b) argue that a fully saturated linkograph indicates no diversification of ideas, hence less opportunity for quality outcomes. This graph shows that when $p(1)$ is between {0.35, 0.65}, H is over 0.93 that is if the links in a row are in between 35% and 65% it will received a very positive value (rich design process). If the links are less then 5% or over 95%, it will receive a very low H value (below 0.29).

In practice it is unlikely a fully saturated linkograph will have more than 7 moves. Figure 10 illustrates a typical linkograph in relation to the saturation of links; there are more *n* to *n-1* links than *n* to *n - i* links.

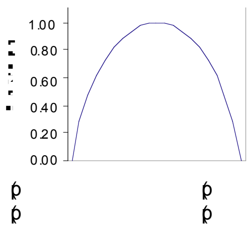


Figure 9. Maximum entropy when p(ON)=p(OFF)=0.5

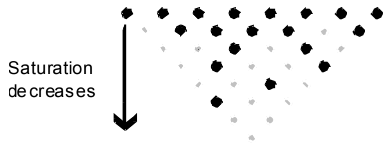


Figure 10. Typical distribution of links in a linkography of a design process

The reason for that is people will try to maintain a coherence of conversation/thought in a conversation (Grice 1975; Pavitt and Johnson 1999) and people have limited short-term memory (Miller 1956).

If we follow Miller's "magic number seven plus or minus two", any rows in a linkograph will seldom have more than 9 links. Taking the 35% linkage as denominator, therefore, any rows with row length more than 26 moves will not have a high H value. This graph resembles the Wundt curve by Berlyne (1971), Figure 11. He used variables such as complexity or what he considered as surprise as stimuli that triggers curiosity.

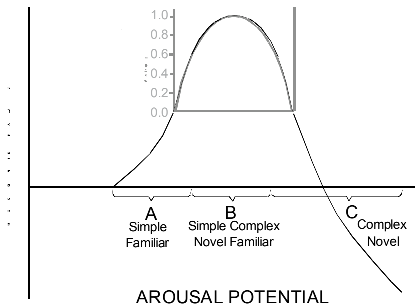


Figure 11. Wundt curve overlay with entropy curve.

Berlyne's theory suggested that if the information received is too novel or too complex the hedonic value will decrease, hence less interesting. Our hypothesis is that ahigher entropy implies a process with more opportunities for ideas development.

4.1. HYPOTHETICAL CASES

Four hypothetical design scenarios with only five moves or four stages are used to examine these concepts further. Table 1 shows some of the possible linkographs together with the interpretation of the design processes they encapsulate. Tables 2, 3, and 4 are the entropy, using formula (3), of the forelinks, backlinks, and horizonlinks respectively. Table 5 is the cumulative entropy which maps well on to our understanding of those scenarios.

TABLE 1. Some possible linkographs of five design moves and their interpretations.

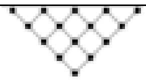
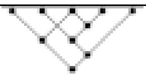
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.
Case 2		All moves are interconnected, this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred, therefore also very low opportunity for novel idea.
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing indicating some opportunities for ideal development.
Case 4		Moves are inter-related but also not totally connected indicating that there are lots of opportunities for good ideas with development.

TABLE 2. Entropy of forelinks

	Forelink Entropy				
	Move 1	Move 2	Move 3	Move 4	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0.811	0.918	1.000	0	**2.730**
Case 4	1.000	0.918	1.000	0	**2.918**

TABLE 3. Entropy of backlinks

	Backlink Entropy				
	Move 2	Move 3	Move 4	Move 5	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0	1.000	0.918	0.811	**2.730**
Case 4	0	1.000	0.918	1	**2.918**

TABLE 4. Entropy horizonlinks

	Horizonlink Entropy			
	n-1	n-2	n-3	**Total**
Case 1	0	0	0	**0**
Case 2	0	0	0	**0**
Case 3	0	0	0	**0**
Case 4	0.811	0.918	1.000	**2.730**

TABLE 5. Cumulative entropy of each case

Case 1	Case 2	Case 3	Case 4
0	0	5.459	8.566

5. Entropy of Face-to-face and NetMeeting Sessions

Table 6 shows the entropy of the Face-to-face and NetMeeting sessions. Forelinks can be seen as initiations and backlinks as responses. So a higher H value of forelinks signifies higher opportunity in initiating design moves, and a higher H value of backlinks denotes higher opportunity in building upon previous design moves. The horizonlink entropy indicates the opportunity according to the length of the links, high values usually indicate a mixture of long and short links which suggests the cohesiveness and incubativeness of ideas. In the Face-to-face session the backlink entropy is higher than the forelink entropy which indicates higher opportunity of building upon than initiating moves. The NetMeeting session scored the opposite, the initiation opportunity is higher than the response opportunity. These match our qualitative analyses of both sessions. In the Face-to-face session they were in the stage of refining the design, referring to what is already there, whereas in the NetMeeting session they started from the beginning, initiating new ideas there. Both sessions have similar horizonlink entropy. Overall, the face-to-face session has a higher entropy in all three areas implying the opportunities are higher in all the areas.

TABLE 6. Entropy of the two sessions.

	Forelinks total H	Backlinks total H	Horizonlinks total H	Cumulative Total H
Face-to-face	34.17	36.69	12.24	**83.10**
NetMeeting	28.00	27.23	11.62	**66.85**

5.1. INDIVIDUAL ENTROPY CONTRIBUTION AND ROLE

Tables 7 and 8 show the forelinks and backlinks entropy contributions by different participants. In both sessions the leaders scored higher than their partners in both forelinks and backlinks entropy. There are two factors that contribute to this: the number of moves and the entropy per move. From our qualitative analysis we know the leaders did most of the drawing, hence contribute more moves. The leaders also have a higher entropy per move except for the forelinks of the Landscaper. This is due to the Landscaper's contribution of an new idea – taking advantage of level changes which is an opportunistic initiation. The individual's entropy score faithfully reflected their opportunistic contributions.

TABLE 7 Forelink and backlink entropy by individuals in the Face-to-face session

	Moves	Forelink H per move		Backlink H per move	
Senior Architect	60	21.661	0.361	22.846	0.381
Architect	38	12.511	0.329	13.847	0.364

TABLE 8 Forelink and backlink entropy by individuals in the NetMeeting session

	Moves	Forelink H per move		Backlink H per move	
Architect	60	16.582	0.276	17.930	0.299
Landscaper	37	11.283	0.305	8.988	0.243

6. Changes of Entropy During Session

As we observe the linkographs of Figures 6 and 7, it is easy to infer that the entropy varies across the time line. There are two approaches to measure this change, one using a fixed time frame as a reference window and the other use a fixed number of moves as the width of window. We use the latter because it is easier to operate and give more meaningful comparison. If we calculate the entropies within a 7 moves window as in Figure 12, we can record the changes of entropy across the design session. In this method we neglect those linked nodes outside the window, which is outside the shaded triangle. The 7 moves cut is indicative rather than conclusive. In the following sections we shall empirically derive a suitable moves window width to get meaningful results. By monitoring the change of entropy we can study the trend of a design session.

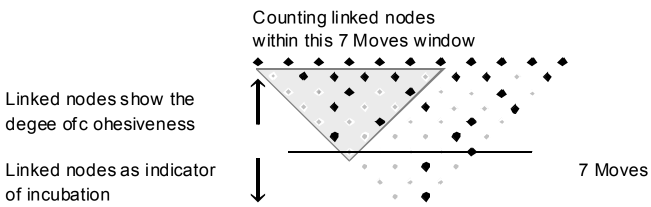


Figure 12. Using a 7 moves window to calculate the entropies.

6.1. DESIGN MOVES AND SHORT-TERM MEMORY

Miller (1956) demonstrated that the chunk of information hold in short-term memory was limited to seven plus or minus two. There are other more articulated models of memory model like Paivio (1986), Baddeley (1986), and Logie (1995, 2001) that use the term working memory rather than short-term memory so as to describe it better. Baddeley's model of working memory contains three parts, the visuo-spatial sketch pad, the phonological loop, and the central executive. Logie's developed Baddeley's model to consider knowledge, long-term memory representation, as a filter that will bias perceptions before getting into the three parts of working memory. It remains that the content of this memory degrades rapidly, in general it is believed it holds information for about 12 to 20 seconds. Important or interesting information will be sustained in the working memory and trigger further associations in the memory system. As we assume that moves are selected externalization of the designers' cognitive processes so as to communicate with their partners, the cognitive processes that correspond to the moves can be in the working memory or in the long-term memory. When these processes are in working memory the corresponding moves will have high interconnectivity.

6.2. DETERMINING THE WIDTH OF MOVES WINDOW

Following Miller's magic number seven, we started experimenting with the change of entropy with a window width of 7. However, this moves-entropy variation is such that it is hard to detect any obvious trend. So we increased the window width to smooth the graph, when the moves window was widen to 28 moves, with the value of the entropy is normalized by dividing it by 28 to produce the average entropy per move, Figures 13 and 14 were obtained. There is a steady increase of all the links entropies in the NetMeeting session at the beginning followed by a shaper raise at the end. In general the Face-to-face session the entropies increase and peak approximately in the middle of the session and then decrease. The horizonlink entropy has two obvious peaks.

8. Conclusion

Studies in design collaboration (Cross and Cross 1995; Gabriel 2000; Olson and Olson 2000; Oslon et al. 1992; Zolin et al. 2004) have shown that there is a multiplicity of factors that contribute or affect the process and product of the collaboration. Some of the factors are: role and relationship, trust, social skills, common ground, organization context, and socio-technical conditions. Most of these factors are underpinned by communication, either verbal or non-verbal, with or without technological mediation. The communication content can serve as a window to observe the individual's cognitive processes (Cross et al. 1996). We selected linkography as a tool to re-represent the communication content and then use entropy to measure the linkograph. The advantages of using linkography are twofold. First, it is scalable in two dimensions, 1) the method is not tied to the number of designers being studies. Goldschmidt (1995) used linkography to compare the processes of three designers with the process of a single designer, and 2) the length of the linkograph can be of any duration. Second, it is flexible in that the design moves and how the design moves are linked can be coded separately depending on the focus of the study (Dorst 2004; Kan and Gero 2004; Van-der-Lugt 2003).

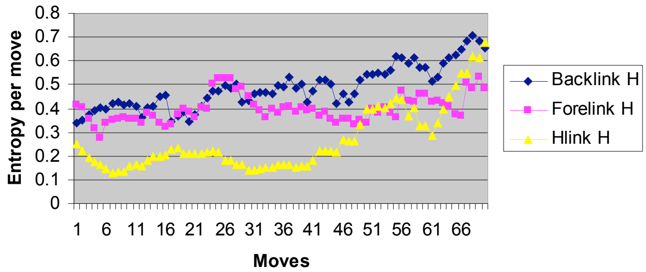


Figure 13. Change of entropy in NetMeeting session with 28 moves as window.

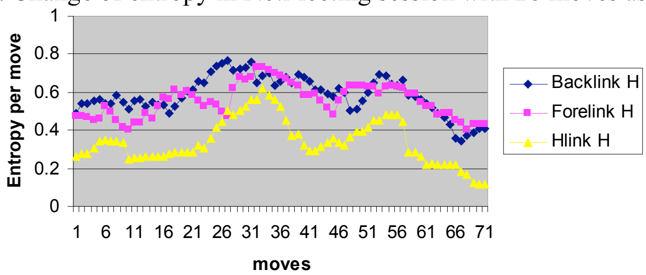


Figure 14. Change of entropy in Face-to-face session with 28 moves as window.

7. Further Investigation of the Change of Backlink Entropy

We further examine these trends by fitting them into a polynomial function. The backlink entropies with 28 moves window were assigned as an array in MatLab. Using MatLab's supervised polynomial fit function, a 4th degree polynomial was obtained, Figures 15 and 16.

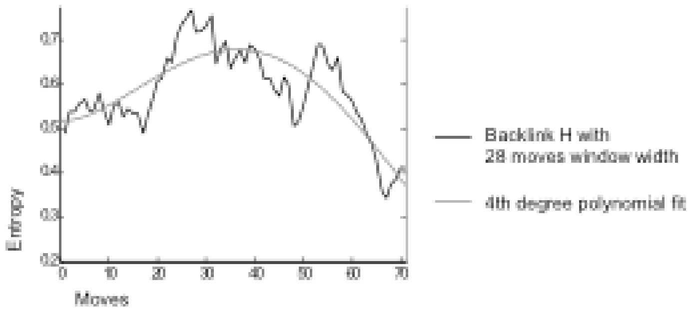


Figure 15. Changes of backlink entropy during the face-to-face session. 28 moves was used as a window for entropy measurement.

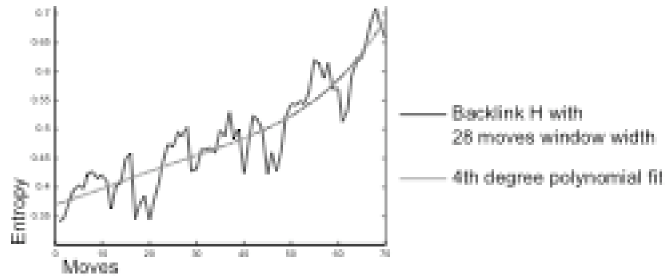


Figure 16. Changes of backlink entropy during the NetMeeting session. 28 moves was used as a window for entropy measurement.

Since the scale of the entropy axis of Figures 15 and 16 is different, we re-plotted the two polynomial curves with the same scale in Figure 17 for comparison. The form of the two polynomials is very different. The rate of change of entropy of the NetMeeting session is always positive while the second half of the face-to-face session is negative, Figure 18. The Face-to-face session has a higher backlink entropy while the NetMeeting session has a higher positive rate of change of entropy. This is confirmed by using adaptive Simpson quadrature in MatLab to calculate the areas of under the curves in Figure 18. The areas are 0.032 for the face-to-face session and 0.162 for the NetMeeting session

In this paper we proposed the use of Shannon's entropy to measure linkographs as an indicator of the idea development opportunity in a design session. We outlined the idea behind this approach and suggested measuring three types of links. Forelink entropy measures the idea generation opportunities in terms of new creations or initiations.

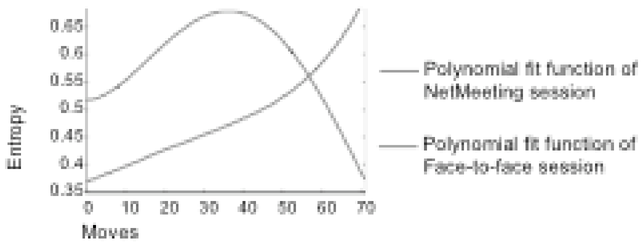


Figure 17. Plotting the backlink entropy polynomial fit of the two sessions with the same scale.

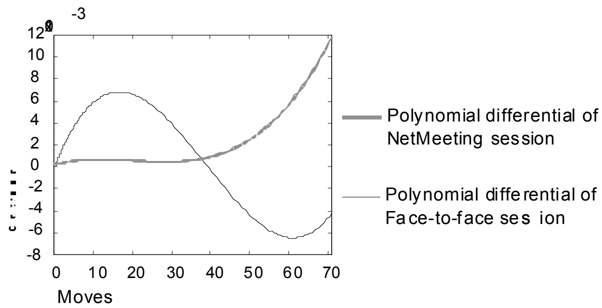


Figure 18. The polynomial differential, representing the rate of change, of the backlink entropy in both sessions.

Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation. We also measured the variations of entropy of these links within a session; it can be observed that the two sessions produced very different shapes of moves-entropy graphs. This can be seen as the signature of a design session. Further investigation is required for discerning the meaning of this signature. For example if the rate of change of the move-entropy graphs is negative, does it mean that it is a converging process since the idea development opportunity is getting less and less? Our approach may form the basis of a new tool to assess designers and design sessions and may provide the opportunity to study the impact of various forms of computational technology on collaborative design.

Acknowledgement

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SESSION FIVE

Individual designing behaviour and learning style: Investigation of the design process of interior design students
S. Bar-Eli

Usage of methods in student projects
S. Schneider & U. Lindemann

Exploring the everyday designer
R. Wakkary

Studying outstanding designers
N. Cross & B. Lawson

JS Gero and N Bonnardel (eds), *Studying Designers'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 249-266

INDIVIDUAL DESIGNING BEHAVIOR AND LEARNING STYLE:INVESTIGATION OF THE DESIGN PROCESS OF INTERIOR DESIGN STUDENTS

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Abstract. This is a short description of an ongoing research carried out within the context of design education. The research is based on an empirical experiment using qualitative and quantitative methodologies, aimed at identifying individual designing characteristics, and demonstrating how they act in unison to form a comprehensive pattern of design behavior, based on the examination of a relatively large population of design students. Subsequently, we intend to identify the relationship between the subjects' learning styles and their designing behaviors, using Kolb's model of learning styles. Focusing on the designer/learner during the design process and understanding his/her behavior advocates a growth model of design education, which will ultimately provide the students with a better awareness and enhance their trust in their personal process.

1. Introduction

Research in the area of individual differences in cognitive and learning styles is based on the theory that these styles are relatively stable attributes, preferences, or habitual strategies used by each individual to organize and process information for the purpose of problem solving (Kolb 1984).

The emphasis in this research is placed on the individual learner and on Kolb's learning style model, which focuses on the learning process, since the design activity can be perceived as an ongoing process of learning and reflection through making, seeing, doing and discovering.

In various studies, Cross (2001), Goldschmidt (2001), Akin and Lin (1995), Schon (1992) Goel (1995) and others made attempts to understand **behavior patterns of designers**. Most of the studies were performed on a small number of subjects and were aimed at defining different characteristics of the design activity. Furthermore, they did not address the issue of how these characteristics act in unison and form a comprehensive pattern of design behavior, based on the examination of a relatively large population of designers.

Research on the relationship between learning styles and design is still in its infancy, focusing on issues such as teaching and learning in the context of the design studio (Demirbas and Demirkan 2003; Kvan and Yunyan 2005) and the use of information in the design process (Newland 1990). The dominant approach in this field focuses on the learning-teaching context, and not on the learner. Moreover, the methodological emphasis is placed on documenting the process of designing using its end results as an analysis tool, rather than the analysis of the process itself.

The three goals of the present research are:

- To identify individual designing characteristics of interior design students;
- To identify the designing behavior of the students, on the basis of combinations of their designing characteristics;
- To identify the relationship between the students' learning styles and their designing behaviors.

2. Learning Style

Experiential learning theory defines learning as "the process whereby knowledge is created through transformation of experience. Knowledge results from the combination of grasping and transforming experience" (Kolb 1984, p. 41).

The ELT model portrays two dialectically related modes of **grasping experience** (perceiving information): Concrete experience (CE) and abstract conceptualization (AC); and two dialectically related modes of **transforming experience** (process information): Reflective observation (RO) and active experimentation (AE).

Each dimension of the learning process presents us with a choice. Since it is virtually impossible, for example, to simultaneously drive a car (CE) and analyze a driver's manual about the car's functioning (AC), we resolve the conflict by choosing. Because of our hereditary inclinations, our particular prior life experiences and the demands of our present environment, **we develop a preferred way of choosing**. We resolve the conflict between concrete and abstract; and between active and reflective in some patterned, characteristic ways. We call these patterned ways "learning styles".

Kolb, Boyatzis and Mainemeils (2001) describe the orientation and dominant characteristics of each style:

The **Diverger** relies primarily on the dominant learning abilities of concrete experience (CE) and reflective observation (RO).

Individuals with this learning style are best at viewing concrete situations from many points of view. This is labeled 'diverging' because a person having this style performs better in situations that call for the generation of ideas, such as a "brainstorming" session. People with diverging learning style have broad cultural interests and like to gather information. Research demonstrates they are interested in people, are imaginative and emotional, have broad cultural interests, and specialize in the arts. In formal learning situations, individuals with a diverging style prefer to work in groups, listen with an open mind, and receive personalized feedback.

The **Converger**'s learning strength is opposite to that of the Diverger's, emphasizing abstract conceptualization **(**AC) and active experimentation (AE).

Individuals with this learning style are best at finding practical uses for ideas and theories. They have the ability to solve problems and make decisions based on the search for solutions to questions or problems. Individuals with the converging learning style prefer to deal with technical tasks and problems rather than with social issues and interpersonal issues. These learning skills are important for attaining effectiveness in specialist and technology careers. In formal learning situations, people with this style prefer to experiment with new ideas, simulations, laboratory assignments and practical applications.

The **Assimilator** relies primarily on the dominant learning abilities of abstract conceptualization (AC) and reflective observation (RO)

Individuals with this learning style are best at understanding a wide scope of information and putting shaping it into a concise, logical form. Persons having an assimilating learning style are less focused on people and more interested in ideas and abstract concepts. Generally, people with this style find it more important for a theory to have logical soundness than practical value. The assimilating learning style is important for effectiveness in careers in the information and science domains. In formal learning situations, people with this style prefer lectures, the exploration of analytical models, and having time to think things through.

The **Accommodator**'s strength is opposite to that of the assimilator, emphasizing concrete experience (CE) and active experimentation (AE).

People with this learning style have the ability to learn primarily from "hands-on" experience. They enjoy implementing plans and getting involved in new and challenging situations. Their tendency may be to take action based on gut feelings rather than on logical analysis. In problem solving, individuals with an accommodating learning style rely more heavily on other people for information than on their own technical analysis. This learning style is important for effectiveness in action-oriented careers such as marketing and sales. In formal learning situations, people with the accommodating learning style prefer to work with others in order to get assignments done, to set goals, to do field work and to test different approaches to completing a project.

As mentioned by Kolb (Kolb et.al, 2001), because experiential learning theory is a holistic theory of learning that identifies learning style differences among different academic specialists, it is not surprising that ELT and LSI research is highly interdisciplinary, addressing learning and educational issues in several fields. Since the first publications appeared in 1971, many studies of ELT and LSI have been conducted. The most recent update of the bibliography of research on experiential learning theory and the learning style inventory (Kolb, A. & Kolb, D.A., 1999) includes 1004 entries. The field classification categories are: education, management, computer and information science, psychology, medicine, nursing, accounting, and law.

3. Design Process and Design Behavior

According to Chan (1990, 60), architectural design is a type of problem solving that primarily involves a series of actions that must be performed in order to solve a design problem, which is characterized as ill-defined.

The design process can be described as a kind of experimentation involving a conversation with the materials of the design situation (Schon and Wiggins, 1992). Research carried out by Schon and Wiggins, as well as by others, like Harfield (1999) and Kruijff (1998), suggests that it is almost impossible to provide a coherent description of the designing, which is applicable to every individual design process, due to the many factors that play a key role in this process, such as the design task; the variety of design methods that can be used; the design tools and media; the environment in which the process takes place and the designer’s experience; the knowledge that the task is based upon; etc.

The design process involves several different stages, from preliminary design to realization and evaluation for future design. This research focuses on the preliminary phase, i.e., the conceptual phase, or what Goldschmidt classifies as the “front edge” (1998, 85). This phase is defined as the phase in which a solution to a design problem is sought at a preliminary, sketchy level. Goldschmidt adds that in this phase designers are engaged in a search in which many ideas and possibilities are typically raised and examined, often to be discarded later.

Focusing on the preliminary stage has theoretical merits. The attempt to relate the design characteristics and behavior to learning style requires placing an emphasis on information gathering and knowledge processing strategies, which are the main focus of the later conceptual phase.

This direction highlights one of the differences between this experiment and prior researches. Demirbas and Demirkan (2003) and Kvan and Yunyan (2005) focused on judging the results of a complete design process for various reasons. Their first objective was to find the effect of learning style on **design studio education**, meaning the teaching strategy used by the studio instructor. The second objective was to find the relation between the **academic performance** and learning styles, focusing on the end product and not on the design process itself.

In the past 40 years we can find a growing interest in research dealing with various issues pertaining to the design process, including descriptive and prescriptive models. We are mostly interested in the descriptive studies that revolve around the characterization of the process in the most general form and the identification of the operations and explicit representations made by the designer, which are responsible for the development of design, solutions, and the description of design tasks within the context of a taxonomy of tasks.

Design behavior is shaped by a combination of **design characteristics**, which generate the individual's native design behavior. We define a **design characteristic** as a single aspect of behavior in the context of designing, which demonstrates the individual's habitual mode of solving design problems. According to Cross (2001, 95-97) patterns of behavior (or characteristics) of design activity can be analyzed according to three main activities: problem formulation; solution generation; and process strategies. Each main activity includes several design characteristics that are the result of in-depth research. The first two are of interest to this research in formulating the basis for the analysis of the experiment.

Problem formulation is a difficult task and requires sophisticated skills of gathering and structuring information. The questions that are raised by researchers are how much attention is devoted during the definition phase of the problem before giving thought to the outcome of the process. Lawson (1990), for example, shows that designers, as opposed to scientists, solve problems through synthesis by immediately proposing a series of solutions and eliminating them one by one, until they find the acceptable one. Schon (1988) established the notion of problem framing and suggested that the designer must describe the problem situation, select the aspects of the problem space that they want to focus on and identify the areas of the expected solution that they want to address.

Characteristics that relate to **solution generation** are fixation; attachment to concepts; generation of alternatives; creativity; and the role of sketching. Some of the questions that were raised by researchers in this main activity of solution generation are: to what extent are designers influenced by prior designs? Are the designers attached to their early ideas and solutions, or are willing to re-think their concepts and search for new concepts? Do 'creative leaps' or 'sudden mental insights' occur during the design process, and in what way do they affect the progress of the process? Iin what way do sketches help to promote the design development?

Suwa, Purcell and Gero (1999) show that design sketches serve as a medium through which a designer makes discoveries; a designer externalizes newly formed, but still vague ideas in the form of a less rigid and ambiguous depiction on paper. By inspecting externalized ideas, the designer finds useful clues to refine them, which motivates him or her to draw again.

Another important characteristic of the design activity is the type of knowledge employed in the design process. The problem solver of ill-defined problems must generate and represent a great deal of additional information (beyond the given) that he or she 'imports' into the problem space, as mentioned by Goldschmidt (1997, 442). This phenomenon of importing information into the problem space is very interesting, since imported information obeys no rules. The information may come from any domain, be represented in any medium, and penetrate any existing information structure, at any point.

Many of the above design characteristics were defined on the basis of comparison between designers from different fields, such as industrial design, architecture and others, such as mechanical engineering. Our aim is to identify the differences within one field of interior design in order to obtain a wide spectrum of attributes for each of the characteristics.

4. Research Hypotheses

Combinations of individual designing characteristics determine consistent designing behaviors.

Individuals' designing behaviors are related to their learning styles.

5. Research Method

5.1 POPULATION SAMPLING

The population of this research consists of interior design students.

We chose students rather than mature designers in order to neutralize the variable of prior knowledge and experience and its possible effect on the individual's designing characteristics.

The students were chosen from two different interior design departments in order to reduce the possible effect of tutorial impact and the department's design teaching focus, and consequently neutralize the effect on the experiment's results. Only students from the second year and above participated as their experience enabled them to relate to and discuss their design behavior.

In both schools, all students were tested to identify their learning styles. Twenty students were chosen for each learning style, producing a total experiment population of 80 students.

5.2 RESEARCH DESIGN

5.2.1 The Experiment

Once the subjects were enlisted, they were requested to participate in a "think-aloud" design problem-solving experiment involving two design problems, each requiring up to 30 minutes to solve.

Individual subjects, seated alone with the experimenter, were presented with a general instructions sheet. The two design problems were presented in written form. The subjects were instructed to work while verbalizing their thoughts, freely using paper and pens to enable sketching and writing. The process was videotaped, with the camera aimed at the working surface. The experimenter did not interview during the session, only reminded the subjects to "think aloud" if they were silent for longer than a few seconds.

After both problems were solved, an interview was conducted, including questions relating to issues such as problems that arose during the design process; how each of the subjects usually relates to stages of the design process and proceeds from one stage to the next; and which part of the process was the most satisfying. The interview results will be used to clarify questions related to the subjects' design processes and in the interpretation of the experiment results, mostly for the in-depth qualitative analysis.

The videotaped materials and the subjects' sketches and writings were used to create protocols, which are currently being analyzed using a coding scheme that pertains to designing characteristics.

5.2.2. Types of Design Problems

In most research dealing with the design process and behavior, the type of design problem, as a key issue of the designing of the experiment, was not thoroughly investigated. The problems were not addressed beyond the definition of ill-defined or well-defined problems. As stated by Goldschmidt (1997, 441) the realization that design problems are ill-structured (or ill-defined, or non-routine, or wicked) has been slow in coming; however today there seems to exist a consensus concerning this observation. Others, like Dorst (1996, 18) outlined basic conditions, such as that the problem should be challenging, realistic, appropriate, not too large in scope, feasible in the time available and within the researcher's sphere of knowledge.

In this research, defining the type of design problems became highly important, due to the fact that each subject had to cope with more that one design task. Two types of design problems were presented to each subject, in order to decrease the effect of the type of problem on the resultant subjects' designing characteristics. The distinction between the types of problems was based on the problems' contents and requirements.

Because the emphasis of this research is on observing the actual process of designing and not the result, it was essential that both design problems will require the student-designer-learner to express personal opinions and beliefs about the problem, promoting questioning and thinking.

We created five design problems, which were presented to five judges requesting them to scale each problem according to criteria relating to problem formulation and solution generation[1]. Analyzing the test results, we found the greatest difference between the problems of the type "Passage" and "Space in exile". As can be seen in Figure 1, "Passage" was the problem that the judges believed to be the most concrete, analytical, encouraging the creation of design rules and using knowledge from the field of design. "Space in exile", as opposed to "Passage" was the most abstract, the less analytical, and encouraging the use of knowledge outside the fields of design. As a result, we used the two problems in the experiment (Table 1 illustrates the problems given to the subjects).

5.2.3 Analysis of Protocols

Protocols are analyzed in order to define design characteristics that will later yield design behaviors. Based on the literature (Akin and Lin 1995; Purcell, Gero, Edwards and McNeill 1996; Dorst and Dijkhuis 1996; Dwarakanath and Blessing 1996), we have composed a preliminary scheme of categories for coding, aimed at assigning design characteristics.

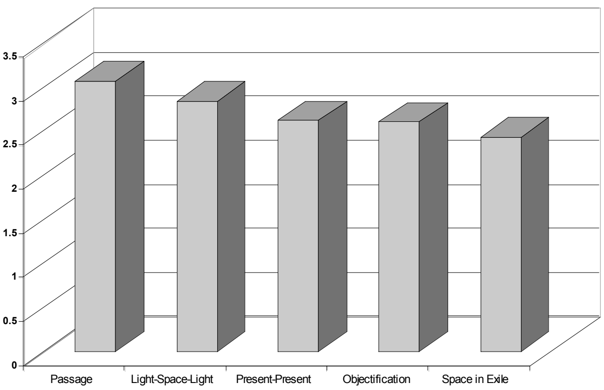

Figure 1. Inter-rated agreement test results (Mean scores of judges scaling)

We began by using a large number of categories for the pilot of the first twelve subjects. The pilot analysis allows us to narrow some categories and add others, and will later allow us to create a coding scheme to be used in the quantitative phase of the research. We attempt to arrive at a number of categories that will allow us to easily observe the relationship between the categories in forming profiles of design behaviors. Qualitative content analysis[2] was preformed on the first twelve protocols in order to find differences and similarities between subjects, which will later be related to their learning style.

5.2.4 Mapping the Relations between the Individual's Designing Behavior and Learning Style

This stage will focus on the relations between the individual designing behavior and learning style. The analysis will relate to the derived designing behavior and to the learning style of each subject. We intend to quantify some of the designing categories being produced at the qualitative stage of the protocol analysis. The importance of the coding scheme as mentioned by Purcell et al (1996, 227) is that it will embody both data and theory generated categories.

Subsequently, we intend to use appropriate statistical methods in which we will map the relations between these categories and the four different learning styles.

5.3 MEASUREMENTS

5.3.1 Measuring Learning Style

We used the Learning Style Inventory (LSI)[3] developed by Kolb (1984) in order to assess the student's learning styles.

The test is a nine-item description questionnaire. Each item asks the respondent to rank four words in a way that best describes his or her learning style.

One word in each item corresponds to one of the four learning modes – concrete experience (sample word: feeling); reflective observation (watching); abstract conceptualization (thinking); and active experimentation (doing). The LSI measures a person's relative emphasis on each of the four modes of the learning process – concrete experience (CE); reflective observation (RO); abstract conceptualization (AC); and active experimentation (AE), plus two combination scores that indicate the extent to which the person emphasizes abstractness over concreteness (AC-CE) and the extent to which the person emphasizes action over reflection (AE-RO).

Our subjects' distribution into the different learning styles is graphically represented in Figure 2.[4]

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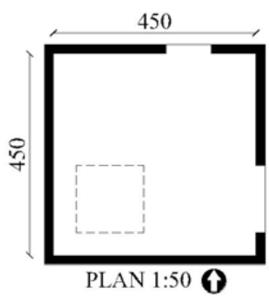
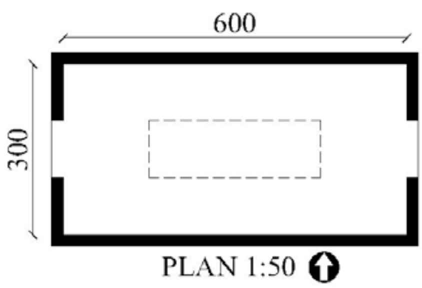
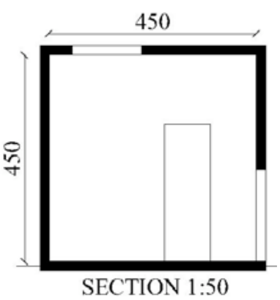
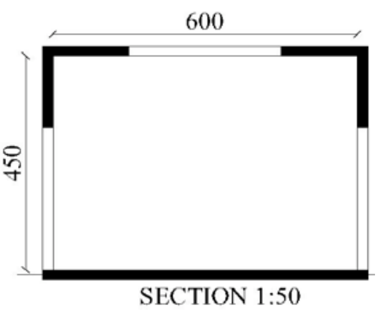
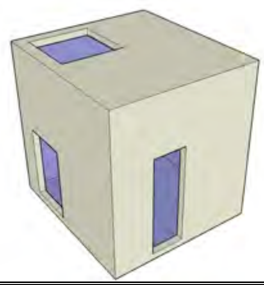
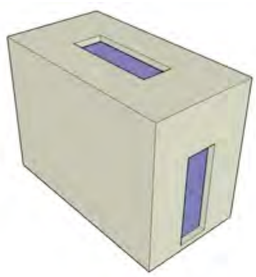
[2] Using "Narralizer"- an Israeli developed content analysis program specified for Hebrew speakers. The program was developed by Shkedi, A (2005)

[3] The LSI was translated into Hebrew and validated by Kats (1988).

[4] After testing 156 students

TABLE 1. Description of the experiment design problems

	Problem I	Problem II
Description	**<u>Given a structure:</u>** 1. See attached drawings 2. Sttached isometric drawing **<u>The exercise:</u>** Space in exile Design the interior space according to the term – "space in exile" **<u>Keywords (example only):</u>** Who or what is in exile? Attach\detach, Return, Separation, Choice, Longing	**<u>Given a structure:</u>** 1. See attached drawings 2. Attached isometric drawing **<u>The exercise:</u>** Passage space Design the interior space to be used as a place for passage. **<u>Keywords (example only):</u>** How to pass? Movement, Rhythm, Direction, Time, Change\transformation
Plan drawing		
Section drawing		
Isometric view		

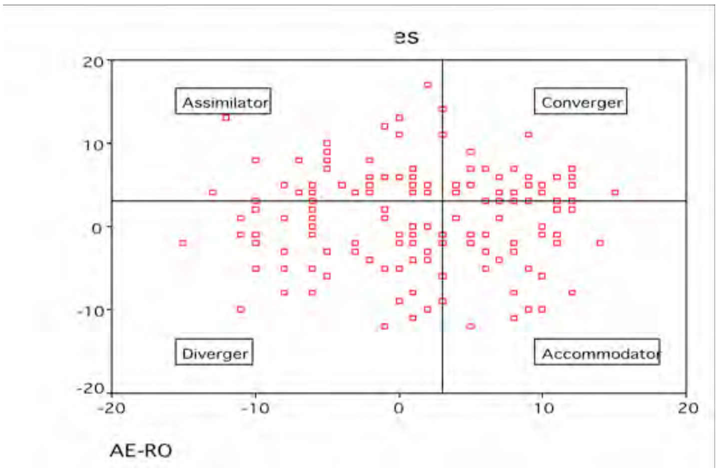


Figure 2. Distribution of subjects' learning styles

Looking at Figure 1, we can see the distribution of the various learning styles with relation to the 156 students that answered the learning style questionnaire. Divergers are 38%, Convergers are 14.7%, Assimilators are 22% and Accommodators are 25.3%.

The distribution shows that all learning styles are evident, and that there is a dominance of Divergers over the rest of the population, and that Convergers are the minority of the four learning styles.

5.3.2 Measuring Designing Characteristics

The categories used for the pilot analysis are based on descriptions and analyses drawn from the design literature. The analysis of the protocol includes different phases: mapping the content of each category regarding each design problem; finding differences and similarities between subjects regarding specific categories in relation to their learning style.

The following is a description of the categories used in the pilot:

Problem formulation:

- Use of data provided
- Problem definition
- Division into sub-problems
- Repetition of data content
- Translation into personal concepts
- Reference to details or to the whole
- Verbalization and visual aids.

Solution generation:

- Solution type
- Developing alternatives
- Re-examining the problem

- From the whole to details (or vice versa)
- From abstract to concrete (or vice versa)
- Working by rules/by visual examples
- Type of examples used in the process
- The appearance of a creative leap
- Design stages (decision making); self-evaluation.

The use of sketches:

- The number of sketches
- Preference to details or to general ideas
- Preferred representation type
- The relationship between the different representation types
- Sheet organization
- Notes writing
- Re-sketching
- Thinking through sketches/verbal thinking

6. Illustration of Category Analysis

6.1 "PROBLEM DEFINITION"

In order to demonstrate our method of protocol analysis, we chose the category of "problem definition". We assume that in this category we can observe the differences between the various learning styles, due to its focus on information processing.

In this example of protocol analysis, we used two researchers (as coders) in order to find the "categories of meanings" included in the analysis of the problem process.

The categories that emerged were:

- Conceptualization of the given problem: what are the various strategies used in understanding the given problem concepts ? ("Passage" and "Exile")
- Referring to the given space: ways of relating to the given data, proportion, measurements, elements, etc.
- Thinking of space functions: what are the possible fuctions that can relate to the generated concept?
- Thinking of a design strategy: what are the chosen decisions that advance the design process?

6.2 RESULTS (12 subject pilot)

6.2.1 The effect of the problem content

As discussed in chapter 4.2.2, the subjects were given two very different problems to design. The "Passage" problem was considered by the judges to be highly concrete, analytical, encouraging the creation of design rules and using knowledge from the field of design, as opposed to "Space in exile", which was considered by the judges to be the most abstract, the least analytical, and encouraging the use of knowledge outside the fields of design. In most of the cases, the difference between the two problems was not fundamental with regard to how the subjects analyzed the problem. When constructing the problems, we assumed that the "Exile" concept might lead to cultural and historical connotations relating to Judaism, the Holocaust, etc. The analysis shows that **Convergers** and **Assimilators** used these kinds of connotations in conceptualizing the problem. This of behavioral aspect was unique to the "Space in exile" problem, meaning that it was not related to the subjects' learning style.

To our surprise, the "Passage" problem created conceptualization difficulties for some subjects, however only for those classified as **Convergers** and **Divergers**. We assume that these difficulties result from the fact that the problem was perceived as "easy", and therefore not requiring a further conceptualizing process.

6.2.2 Conceptualization of the given problem

We found that several different strategies used in conceptualizing the problem related to the subjects' learning style.

Divergers tended to use translation of the key word into personal words/concepts combined with the creation of clear ideas/stories. During the "Space in exile" experiment, J. said: *"I'm looking at the key words…..I find the exile is choice…. And the outcome is essentially an automatic seperation and longing…. The outcome after that has to be return. Following the choice there is attach and detach".* After using the key words when translating the problem concept into his own personal concept, J. creates an idea to further develop the solution, *"If the space was my space I would have liked to use my own sources. Not to create a space that belongs to a different country and a different culture, a very Israeli space".*

The only repeat pattern of conceptualization that was identified among **Convergers** was the translation of the key word into abstract images, in the form of sketches. We found that **Convergers** tended to be influenced by the problem content, i.e., using cultural connotations in the "Exile" problem and claiming that the "Passage" problem *"…is too clear. As if the direction is too obvious, so what is the catch?"*

We found that **Assimilators** tended to translate the key word into a personal word or concepts and, like the **Convergers**, into abstract images; however, we detected a great deal of confusion and indecisiveness in their translation process.

The **Accommodators** also translated the key word into a personal word/concept, however they also used examples, images and analogies from the design field and from reality. When tackling the "Exile" problem E. said:

"Things that feel like, that I was there: like the tour we had in Mario Botta's synagogue at Tel-Aviv University, which has a space of a circle and rectangle that switches and changes. Its seems like it can be an idea of change."

6.2.3. Referring to the given space

The protocol analysis shows that there is no unique pattern among **Convergers** and **Accommodators** regarding the subjects' relation towards the given space. Among these learning styles, subjects used an analysis of the space, relating to specific elements and/or measurements, or paying no attention to the given space.

Assimilators tend not to pay any attention to the space. If any attention is being paid, it is very vague: *"Those holes just make me want to shut them somehow."*

Divergers, on the other hand, always pay attention to the space, however it varies between vague attention and an analysis of the space: *"I have a space with three openings, one upright one in the corner of the room. The entrance door to the space and a lower opening ... here we have a space with six sides, three of them with openings."*

6.2.4 Thinking of space functions

Accommodators have no unique tendencies regarding functionality.

We found no evidence of **Assimilators** and **Convergers** mentioning the issue of functionality. On the contrary, **Divergers** have a strong tendency of referring to optional functions of the space: *"Passage space which is a lobby. Passage is used as a place for a short duration for people. They pass through it as a passage from one place to another"*.

6.2.5 Thinking of a design strategy

Among **Divergers** and **Accommodators** we couldn't identify any unique patterns associated with design strategies. **Assimilators** tend not to develop a clear design strategy*:"Every time I find that I reached something a bit more sophisticated, I try to develop it, to see what I can get out of it"*. In contrast, **Convergers** tend to develop a design strategy, but the extent of vagueness or clarity of this strategy depends mainly on the problem content. The "Passage" problem encourages the creation of a clear design strategy, such as changing the space in a certain way. The "Exile" problem, on the other hand, leads to abstract strategies such as *"puzzle"* or *"a form inside a form."* Results are illustrated in Table 2 below.

6.3 DISCUSSION

Although we have only illustrated one category analysis, our findings suggest the existance of consistent tendencies of design characteristics (patterns of behavior) that relate to subjects' learning styles.

Divergers, who were profiled as better in situations that call for the generation of ideas, were the ones that conceptualized the problem through the creation of ideas/stories. They were also profiled as having the ability to turn a concept into a useful solution. In this research, they were the only ones that always paid attention to the given space and were able to identify adequate space functions.

Convergers, who were characterized as systematic and decisive, demonstrated those qualities in this research by always generating a design strategy. The difficulties they encountered in conceptualizing the problem can be perceived as resulting from other characteristics of their learning style, such as their inability to translate information presented in a non-structured, illogical way.

Assimilators, profiled as indecisive abstract thinkers – traits that can be found in the way they conceptualized the problem, translating into abstract images, accompanied by repeatedly verbalising expressions.

Accommodators, who were profiled as using analogies in their information proccessing, showed this characteristic by using examples, images and analogies from the design field and from reality in their conceptualization process. Accommodators were also profiled as adaptive and flexible; this trait manifested itself in not having a limiting pattern when referring to the space, finding functions and generating design strategies.

From this analysis we can learn that learning styles influence design characteristics in inconsistent ways. As demonstrated in Table 2, the **Divergers'** learning style creates behavioral paterrns that govern the subjects' conceptualization of the given problem, referring to the space and thinking of the possible space functions. In contrast, the **Accommodators'** learning style seems to influence the conceptualization phase only. One must ask if the unpatterned behavior of **Accomodators** results from a lack of influence of their learning style or from its adaptive nature. When behavioral patterns emerge, one may suggest that this is the influence of a specific learning style. The methodological challenge remains how to interpret situations in which no clear behavioral pattern is perceived.

TABLE 2. Illustration of results

	Diverger	Converger	Assimilator	Accommodator
Conceptualization of the given problem	**Translation the key word into a personal word/concepts combined with creating clear ideas/stories**	**Translating the key word into abstract images; Influenced by the problem content.**	**Translating the key word into a personal word or concepts and abstract images (confusion and indecisiveness)**	**Translating the key word into a personal word/concept; Using examples, images and analogies from the design field and from reality**
Referring to the given space	**Paying attention to the space; Varies between vague attention and analysis of the space**	**No unique pattern**	**Not paying any attention/vague attention**	**no unique pattern**
Thinking of space functions	**Always**	**Never**	**Never**	**No unique pattern**
Thinking of a design strategy	**No unique pattern**	**Always (type depends on problem content)**	**Never**	**No unique pattern**

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USAGE OF METHODS IN STUDENT WORKS

Enhancing the use of methods by studying students

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Abstract. Methods in engineering design enhance development processes what was stated in a lot of research projects. Nevertheless there is a big lack of method implementation in industry. Engineers (mostly) learn applying methods at university. To enhance the use of methods in industry it is necessary to analyze the learning process of students. Therefore in this study several student works were analyzed regarding their use of methods. ´First a broad analysis was carried out. Afterwards best cases were analyzed and action proposals derived.

1. Introduction

Methods for engineering design enhance the product development process. This was proved in several research projects (Ambrosy, 1996; Schneider, 1999; Stetter, 2000; Viertlböck, 2000). Nevertheless method implementation in industry fails quite often (Araujo, 1996, Grabowski at al., 1997) what can be seen in Figure 1.

Students should learn and apply methods at university for a later implementation in industry. Hence a set screw to enhance the use of methods in industry is to analyze the learning process of students, find out the characteristics of best practice cases and to derive action proposals. So 70 student works were analyzed according to the number and kind of used methods. Afterwards some examples of excellent student works were analyzed to derive success factors.

At the moment there is some research in the field of user-suitable transfer of methods (Jaensch et al. 2003), nevertheless this is limited to lectures (Jaensch et al. 2004)

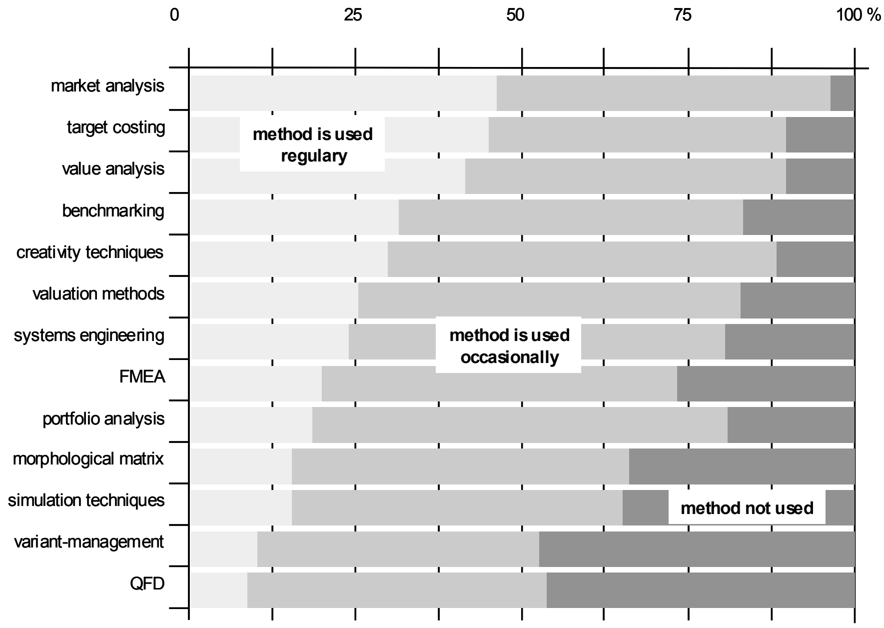

Figure 1. Use of methods in industry (Grabowski et al., 1997)

2. Investigation of student works

2.1. BOUNDARY CONDITIONS

In student works the students should apply their knowledge learned in lectures in a concrete project. The topic is suggested by the supervisor, but the student can choose the proposal. There are two different kinds of student works: "Semesterarbeiten" have to be done during the study (5^{th} to 8^{th} semester), the Diploma thesis has to be led through at the end of the study. Beside the students can learn the theoretical background in two main different lectures:

In "Methods for the Product Development" the use of methods in a product development process is presented.

"Product Development and design" describes the design part of product development.

There are also other lectures, but they are not so important concerning this study.

At the beginning an extensive analysis of student works was carried out. The following points were analyzed:

- Kind of methods
- Number of methods in a work

2.2. RESULTS

The following results were observed in this analysis.

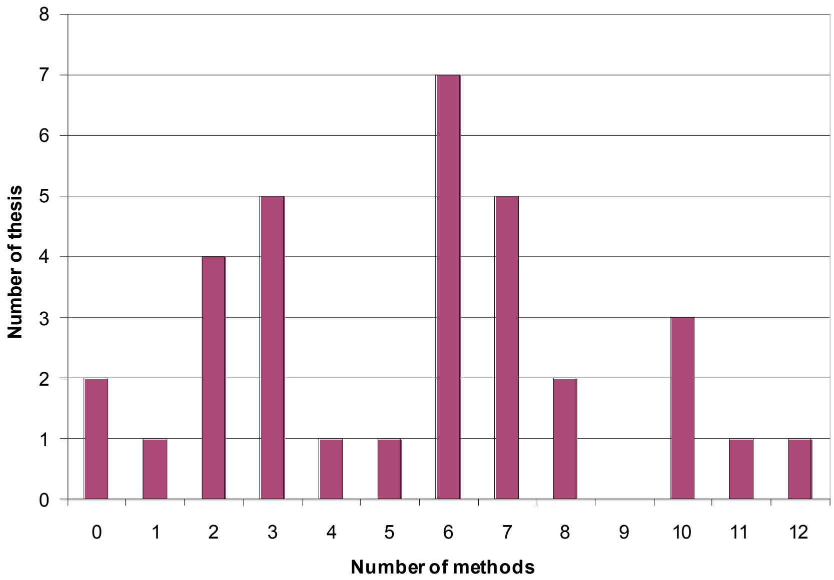

Figure 2. Number of methods used in a "Semesterarbeit"

In most works the number of implemented methods is six or less according to Figure 2. Only very few students have used a lot of different methods. Beside when considering Figure 3 the kind of methods the following characteristics can be noted:

- The methods are quite simple (i.e. list of requirements, brainstorming, morphological charts)
- There is used only one method per problem step (i.e. brainstorming for the search for solutions)
- There are always the same, (necessary) methods used (i.e. list of requirements (what should be basis for all works), morphological charts (basis for a good documentation of the search for solutions), brainstorming, and checklists).
- More complex methods like TRIZ or QFD are only used seldom.

Usually student's works offer the students to test methods with a lot of time and the possibility to fail what is not possible in industry later. So it is amazing that they use so less methods.

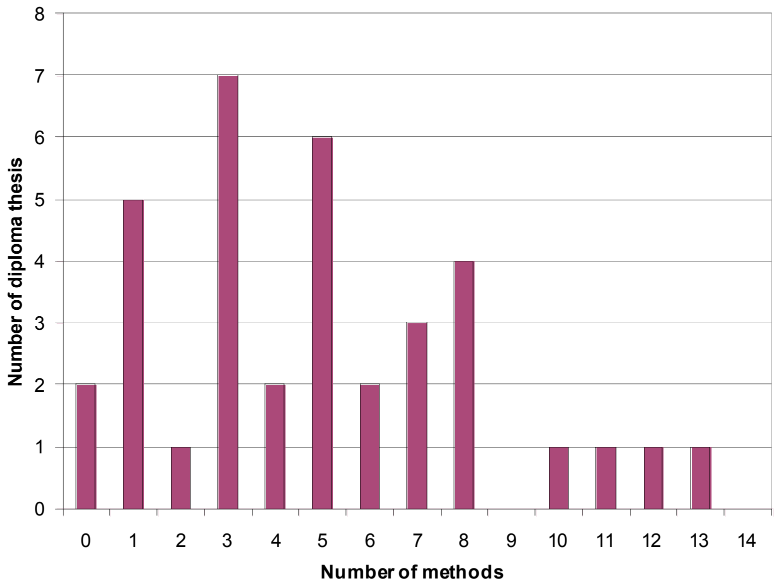

Figure 3. Number of methods used in a Diploma thesis

Another conclusion concerns the reflection about the use of methods. The thesis of the works was analyzed according to the documentation of the method implementation (part in the thesis, degree of reflection about the method implementation (only documentation/ own experiences). In contrast to bad students excellent students document beside the general description of the method also their own experience with the selection, adaptation, implementation and result of the method. This shows the higher degree of reflection about the implementation of methods which is basis for a flexible use of methods.

2.3. CRITICAL CONSIDERATION OF THE RESULTS

The number of methods depends also on the characteristics of the product and the problem, so the number of methods used in the works is only a rough criteria. Nevertheless this was the only possibility to analyze the use of methods in abroad number of works.

There is no senseful analysis of the correlation between number of methods and degree possible. This has two reasons: First the degrees of the works are general excellent, so there is no real difference. Second the degree depends on the supervisor and his criteria for the evaluation, which are not only limited to the use of methods. It is also not possible to evaluate the results senseful now, as it is not clear what the exact task was, which exact boundary conditions prevail, under which the work was carried out.

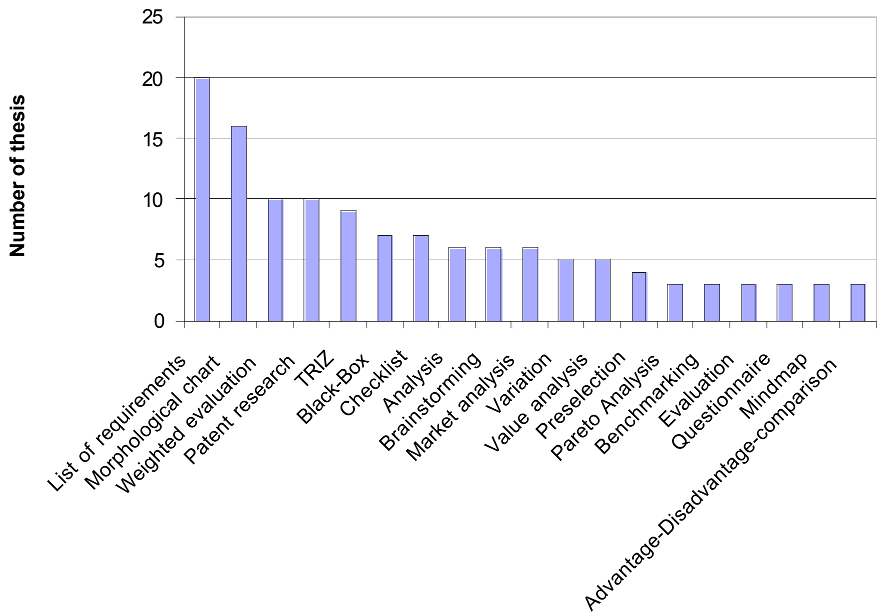

Figure 4. Kind of methods used in a "Semesterarbeit"

3. Best-Practice-Case analysis of excellent student works

Then some excellent student works were analyzed, in this paper only one will be described where the results could be shown very detailed. The aim of the work was the development of concepts for an inspection machine. At the beginning the student made a rough plan how to proceed in the whole project and which methods could be used in the different steps. Of course, due to the progression of the project changes occur and the procedure as well as the methods had to be adapted. Also out of the discussions with the supervisor changes and supplements resulted. But in the whole the student mostly followed the rough plan of the beginning. Besides the planning of the procedure leads to a more effective and efficient execution of the work; better results can be expected in less time. Another result can be derived when analyzing the several steps of the procedure. Exemplary the search for solutions is shown in Figure 6.

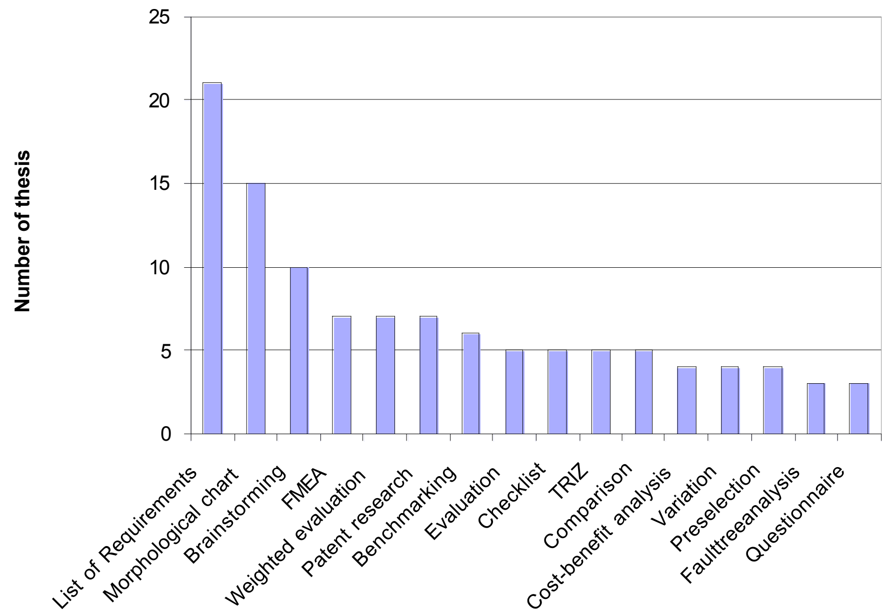

Figure 5. Kind of methods used in a Diploma thesis

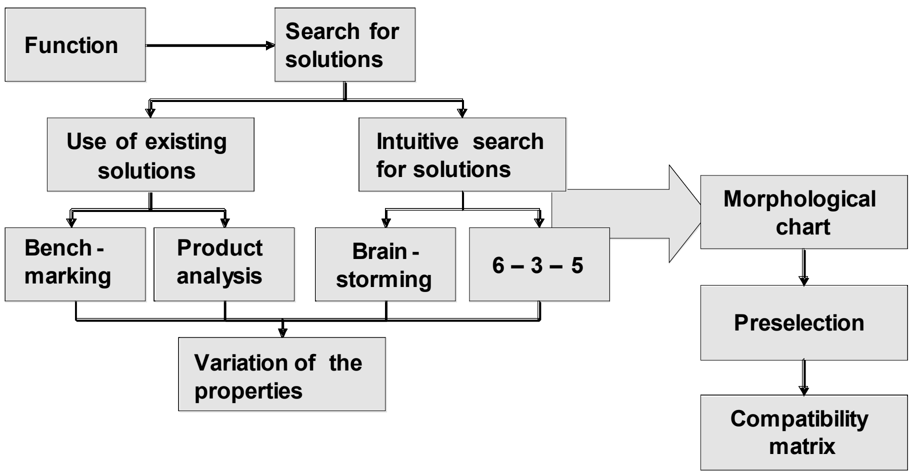

Figure 6. Procedure and methods in the search for solutions

It can be seen that the student uses a lot of different methods for this step. Only by the right interaction of the different methods the necessary variety of solutions can be reached: the benchmarking and the product analysis deliver a lot of existing solutions, creativity methods like brainstorming or 6-

3-5 lead to new alternatives, and all can be systematically supplemented by varying the collected solution alternatives.

Another interesting point is the selection and adaptation of methods: the student analyzed the situation and the corresponding boundary conditions and derived several possible methods for the situation. With this information he made the decision. For example at the end of the projetc after concretizing the concept the student was not sure if the whole concept would be working (without faults). So he decided to carry out a FMEA. To get information and regard the concept from different point of views he decided to invited people from different division: development, electronics, analysing software, service, and the supervisor as not-involved. As no one knew the new concept he prepared and held a presentation the technical details at the beginning. Then the (for this case) prepared and adapted formular was filled out. So the result of the FMEA was satisfying.

4. Action proposals of best practice cases

Out of the conclusions made in the analysis the following action proposals can be made. For the selection and adaptation an adapted "Vorgehenszyklus" (according to Ehrlenspiel, 1995), which will be described below (see Figure 5), can be suggested.

For selecting the right method for a situation/ problem first of all the boundary conditions should be clarified:

- What kind of design do we have (i.e. new development, variant development, …)?
- In which stage of the design process are we?
- What concrete question should be answered?
- Which benefit do I expect from the method?
- Which defect could occur when not using the method?
- Which and how much resources (time, persons) are available or am I willing to spend?

These are some exemplary questions which should be answered to concretize the problem/situation. Then possible methods for the described problem should be searched. Hereby especially the stage of the design process and the concrete question can lead to the interesting methods. It should be mentioned that in a first step a lot of methods should be selected without looking if they are really senseful or not.

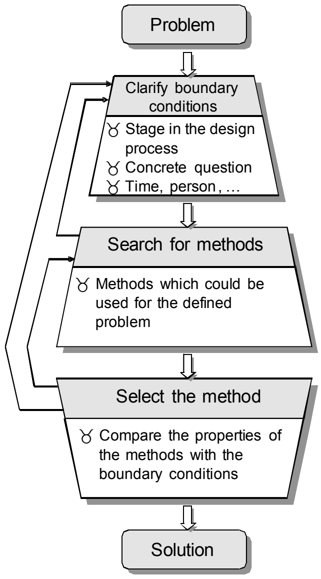

Figure 5. “Vorgehenszyklus” for the use of methods

In the next step the proposed methods should be evaluated according to the boundary conditions, which were defined in the first step. With this information the right method or method mix will be selected.

After the use of the methods the method implementation should be reflected and documented. Hereby the following points should be noted:

- Description of the situation in which the method was used
- Possible methods for this situation
- Selection of the method (Reasons)
- Adaptation of the method to the boundary conditions
- Implementation of the method (positive experiences, problems)
- Result of the method (benefit for the work)
- Interaction with other methods

With reflection the students learn the procedure of the method implementation and identify the decisive points.

5. Conclusion

For better understanding the lack of use of methods in industry an investigation about the use of methods in student works was carried out. In a broad analysis of student works the use of methods and the reflection were analyzed. In average also students use only few and very simple methods. Excellent students use a lot of methods also for the same problem step and reflect quite intensive about the implementation. Out of best cases action proposals were derived which should be applied in student works. Of course they can also be a guideline for the use of methods in industry.

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JS Gero and N Bonnardel (eds), *Studying Designers '05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 277-282

EXPLORING THE EVERYDAY DESIGNER

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Abstract. This paper discusses our preliminary analysis of how designer and non-designer participants discussed and engaged in design activity. For this research, we employed two design study experiments that included a total of forty-eight participants. In our preliminary findings we found differences between designers and nondesigners in how a design activity is analyzed. The more significant preliminary finding is that there were substantially less differences in how designers and non-designers engaged our design activity

1. Introduction

In our research we explore how people, designers and non-designers alike engage in design. Our interest in this study is as designers who want to explore the idea of the everyday designer as someone for whom we design. An everyday designer has no formal design training but through interaction with existing designs modifies or creatively extends these into new designs and uses. We ask to what degree people carry tacit knowledge of design activity and how we as designers might respond? At this stage of our studies our aim is to identify commonality of action in engaging design activities between designers and non-designers such that we can better describe the attributes of an everyday designer, and ultimately develop an approach to end-user interaction modeled after the attributes of everyday designing.

Our current study is in progress. We have analyzed how our designer and non-designer participants discussed and engaged in design activity. For this research, we employed two design study experiments that included a total of forty-eight participants. In our preliminary findings we found differences between designers and non-designers in how a design activity is analyzed. We feel this accounts for why we rarely consider our end-users as designers. The more significant preliminary finding is that there were substantially less differences in how designers and non-designers engaged our design activity we assume that walking the walk is of more consequence than talking the talk.

We feel these studies are important in suggesting how everyday designers can potentially utilize design outcomes as design resources for further design. This type of design activity can be seen as an integral aspect of a deeper cycle of interaction and adaptation that occurs over time and supports the evolution of design systems, artifacts and interaction models. Our view of interaction design is of a practice in which design interventions support the roles of people, artifacts and situated contexts that together form a generative and sustainable ecology of ongoing design responses. Designers intervene as originators or catalysts in a wider circle of people engaged in design activity including the people for whom we design.

The everyday complexity of ubiquitous computing in the home highlights the possibility of a continuum of designers involved in design activity. Current design ethnography suggest the home is a set of organizational systems and routines upon which designers should consider evolutionary solutions (Crabtree et al., 2001). Artifacts and actions in the home are utilized by being made visible, invisible or pliable – they are seen as resources for further action (Taylor and Swan, 2005, Blythe and Monk, 2002, O'Brien and Rodden, 1997, Tolmie et al., 2002). This view strongly suggests the ongoing presence of designers. We can see home dwellers as a type of everyday designer who remakes or modifies organizing systems, and who use design artifacts and actions around them as design resources.

2. Relevant Work

The idea of an everyday designer is not new, for example Fischer has argued for a meta-design approach in software systems (Fischer, 2000). However, unlike meta-design, which argues explicitly that an end-user is a designer that requires design tools to facilitate use, we see interaction with design outcomes as part of an ongoing cycle of interaction in which design action is an integral part. In other words, people have been redesigning our designs all along. For example, Alexander (Alexander, 1964) discussed what he called the unselfconscious process. He describes a design system that maintains equilibrium through constant actions over time (in the generational sense). Actions taken by any individual who could simply recognize a failure and could react in a corrective way. Alexander would eventually describe the process of continuous adaptation as piecemeal growth (Alexander et al., 1977). Louridas's concept of designer as bricoleur describes a continuum of activity that is strongly inclusive of the everyday designer (Louridas, 1999). Designers like bricoleurs, make do with resources available to them and explore the situation through action for new uses and connections. In many respects, the basis of Louridas concept, Levi-Strauss's bricolage explains in anthropological terms the everyday scientist (Lévi-Strauss, 1962). Such processes rely on the tacit knowledge of non-designers to act on the design system. Schön in his paradigm of reflective practice argues for a tacit level of understanding of design, termed knowing-in-action. The designer shapes the design situation through concurrent evaluation and experimentation based on “the intuitive knowing implicit in the action (Schön, 1983). Who has this tacit knowledge?

Little research has been done studying non-designers designing while significant research in analyzing design activity of designers has taken place (Bly, 1988, Cross et al., 1996, Maia et al., 1995, Valkenburg and Dorst, 1998, Adams et al., 2003). Particularly relevant research for our study included Reymen’s empirical analysis of design activities across design disciplines utilizing Schön’s reflective practice as a meta-framework (Reymen, 2001). Application of Schön’s paradigm can also be found in Valkenburg and Dorst description method that is utilized to support a protocol analysis of design activity (Valkenburg and Dorst, 1998), as well as Adams’ study of engineering practice (Adams et al., 2003). Similar to the methods above, we utilized Schön’s paradigm of reflective practice for coding our protocols (Schön, 1983).

3. Experiment Design and Methods

For our studies, the design activity is based on the goal of designing a new game from two existing board games. In our first study we asked participants to watch a videotape of two sessions of two different individuals engaged in our design activity and to describe and interpret the process. We asked the individuals on the video to think-aloud as they were designing. We’ve analyzed the transcripts based on a coding approach for problem definition space used by Adams (Adams et al., 2003). We found their study of freshman and senior engineering students a valuable point of reference related to the differing experience levels of non-designers and designers (Adams et al., 2003). We modified the two codes, “knowledge” and “system” to suit our design activity. We also created a multi-dimensional approach whereby we represent the problem definition space across three dimensions: “description”, “interpretation” and “judgment” (see figure 1). We took this approach to accommodate for the breadth of commentary and representation of the design space.

Our second study involved participants who as a pair were either designers or non-designers. We asked each pair to design a new game from two existing board games chosen from a collection of games we provided. We left the participants alone and allowed them approximately forty-five minutes for the activity. Working in pairs allowed us to address a more typical collaborative deign situation and eased the think-aloud issues since pairs normally verbalize and communicate as they collaborate.

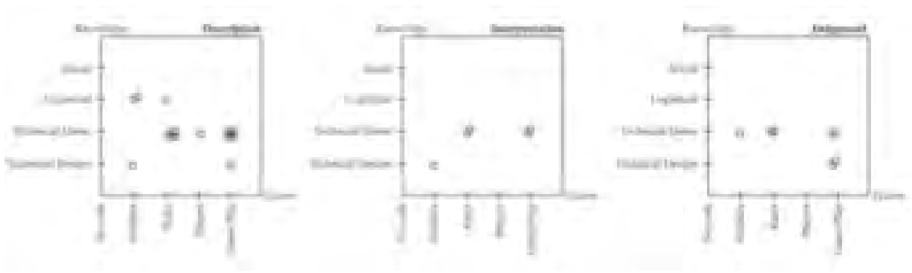

Figure 1. Sample of the analysis of participant (V11) using our multi-dimensional representation of the problem definition space based on Adams (Adams et al., 2003).

It was required that the pairs had prior working experience in order to eliminate issues of new team dynamics and lack of familiarity of work styles. Our analysis employed a modified version of Valkenburg & Dorst’s description method for protocol analysis based on Scho□n’s reflective practice paradigm (Valkenburg and Dorst, 1998). The method analyzes design activity as including the following actions: naming, frame, moving, reflecting. In order to further compare between paired participants we’ve used design activity timelines that map instances of each of the design actions along a timeline.

4. Preliminary Analysis and Ongoing Research

This research is currently ongoing and therefore we can make no conclusions or state findings as being other than preliminary. We are in process of analyzing the data of both studies and validating each of the protocols with at least two independent validations by other experts followed by a consensus discussion to resolve differences. We aim to complete the research in early Fall 2005. At this stage we have completed the studies with twenty-four participants in each study for a total of forty-eight participants. We have completed a non-validated analysis of study one mapping the problem definition space. Adams found that senior engineering students listed more factors and covered more of the problem definition space than freshman students. Our preliminary analysis points to similar findings between designers and non-designers. The multi-dimensional approach reveals that non-designers tend to focus their comments primarily on a descriptive level however they also comment more frequently than designers in areas of judgment, especially on factors of “game play” and “social” aspects. We are currently processing the protocols for study two and we feel we require conversion to design activity timelines in order to better describe common patterns between the paired designers and non-designers. Our preliminary finding is that the protocols are considerably similar showing less of a gap than Adams found in the design activity timelines between freshman and senior engineering students.

5. Summary

Our research at this phase provides a theoretical context supporting the notion of design as a common activity. We have reviewed related studies and methods analyzing design activity. We have designed novel studies for researching analysis and engagement of design activity. We aim to provide a complete discussion of the findings of the studies as soon as the research is completed, as well as its design and research implications. We feel this research will contribute by providing a set of attributes for an everyday designer and show how these attributes relate to designers such that we can provide an alternate view of people as belonging on the design continuum with designers in a generative and ongoing cycle of design responses.

Acknowledgements

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JS Gero and N Bonnardel (eds), *Studying Designers '05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 283-287

STUDYING OUTSTANDING DESIGNERS

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Abstract. The authors have previously made separate studies of outstanding and exceptional designers. In this paper we bring our studies together for comparison and to seek commonalities. We claim that it is important to study outstanding designers for a deeper understanding of design cognition, and we consider some of the methodological issues in the study of outstanding designers. We outline a developing view of expertise in design which has its own particular features, distinct from models of expertise derived from other domains.

1. Why study outstanding designers?

Many studies of designer behaviour are based on novices (e.g. students) or, at best, designers of relatively modest talents. This is because of the easier availability of such subjects for study. It is difficult to gain access to designers of outstanding ability, but studying such designers gives us different insights and understanding of design activity. It is like studying chess masters rather than chess novices in order to gain insight of expert cognitive strategies in chess playing.

The aim of studying outstanding designers is to gain knowledge of design activity at the highest levels at which it is practiced. This knowledge might enable us to transfer and diffuse 'best practice' more widely across the design professions, thus raising general levels of performance. It could be useful for education, in guiding pedagogy towards the development of better-than-average designers. It could aid the design of support tools, not only for the outstanding designers themselves, but also in providing enhanced methods of practice for all designers.

Outstanding designers can be expected to work and operate in ways that are at the boundaries of normal practice. Studying such 'boundary conditions' may provide more significant results and an extension of understanding that is not available from studying average designers. Exceptional cases may provide a clearer view on differences between working practices, rather than the everyday commonalities.

Outstanding individuals in any field can often provide insights that are more extensive and informative than those of average-ability individuals. They are therefore a rich source of new ideas and alternative perspectives. Studying average and novice designers may well limit our understanding of design activity, holding back progress in design methodology, and leading to weak or even inappropriate models of design cognition.

2. Levels of expertise

Studying outstanding designers falls into the more general field of studying expertise. Generic models of expertise generally define a progressive series of levels of attainment. In such models performing at the lower levels is seen as a prerequisite for moving on to the higher levels. Thus the development of expertise within an individual passes through different phases. A novice undergoes training and education in their chosen field, and then at some later point becomes an expert. For some people, the 'expert' level of achievement is where they remain, perhaps with some continued moderate improvement before reaching their peak and beginning their decline. A few manage to go beyond the level of their peers, into a further phase of development, reaching outstanding levels of achievement and eminence.

The levels of achievement are usually seen as plateaux in the time versus performance curve. An important reason for this plateau-plus-increment series of phases is probably because the acquisition of a certain amount of knowledge or experience enables insight to a new way of operating or perceiving. The acquisition of skills seems generally to proceed in this way. Thus these models suggest that operating at higher levels of expertise is not just a matter of working harder, better or faster, but of working differently. To understand expertise fully, therefore, we need to study these 'different' ways of working at the highest levels.

Drawing upon the generic models of levels of expertise, we propose a seven-phase model of the development of expertise appropriate to the context of design. (This model is developed and explained further in Lawson and Dorst (2005).) These phases are: naive, novice, advanced beginner, competent, proficient, expert, master, and visionary. We have been fortunate to have been able to study a number of outstanding designers in architecture, engineering and industrial design, who have achieved the expert and master levels, and even the visionary level of development.

3. Methodological issues

In order to study outstanding designers it is first necessary to have a means of identifying 'outstanding' designers. We have chosen designers who have a clearly acknowledged record of success, including the receipt of professional awards and peer-group recognition. Some of our chosen designers have an objective record of their level of achievement (e.g. designers of successful competition vehicles).

Studying outstanding designers is particularly problematic because of their limited availability as participants. The majority of studies of outstanding designers are based on interviews, because that seems the only way to gain access. However, this technique does have its advantages – it gives a 'rich picture' rather than formalised data, enables cross-project comparisons to be discussed, and enables insights to emerge that were not in the researcher's prior assumptions. Shortcomings of the interview method include being very time-consuming (in post-interview transcription, etc.), a lack of strict comparability between studies, and sometimes there are attributability and commercial confidence problems relating to the design projects that are discussed. The personal recollections of the participants are sometimes poor on time sequences of events, and may be influenced by a variety of factors that may be incidental to the researcher's purposes (e.g. difficult relationships with clients, or financial problems of projects). Participants may post-rationalise their accounts or attempt to fit them to conventional (or idiosyncratic) wisdoms or philosophies of design activity.

Participants may be unwilling to volunteer for interviews, particularly if they doubt the credentials or purpose of the researcher. In our experience, it is essential that the interviewer is familiar with the record of projects of the designer being interviewed. This means a very full prior search on the designer's history. Interviews are best held in the normal work-location of the designer, where the designer can relax in familiar surroundings, and project histories and examples are to hand. A brief, prepared interview guide helps, and must allow for conversational drift and serendipity. The interviewer needs to be familiar with the cultural and technical domains of the designer, so that the discussion can proceed naturally and the designer can assume some shared understanding with the interviewer.

More than one interview is normally necessary, because of the total time needed, and it can be useful to return to the designer after a rough analysis of the first transcript. Ideas and quotes can be fed back to the designer for further reflection. We have found that our interviewed designers can often find the experience pleasant and helpful, particularly if they find they also can learn from the reflective conversation with the researcher.

4. Comparison of studies of outstanding designers

The authors have previously conducted separate studies of outstanding designers – one set of studies being in architecture, and the other being in engineering and industrial design. Here we attempt to bring our studies together, to form a more general overview of design cognition at its highest levels.

Lawson (1994) made a series of interview and observational studies of outstanding architects. He found many similarities in their ways of working, and also some differences. For example, some of the architects prefer to generate a range of alternative solution concepts, whilst others will focus on a narrow range or just one concept. Something they all seem to have is an ability to work along 'parallel lines of thought' – that is, to maintain an open-ness, even an ambiguity, about features and aspects of the design at different levels of detail, and to consider these levels simultaneously, as the designing proceeds. One message that recurred from these studies was the extremely demanding standards set by the designers themselves – outstanding expertise is fuelled by personal commitment.

Many findings in Lawson's studies of outstanding architects resonate with those from studies of outstanding designers in the fields of engineering and industrial design by Cross (1996, 2001, 2003). Cross made protocol and interview studies with three outstanding designers, and drew conclusions on the common aspects of their design strategies. Firstly, all three designers either explicitly or implicitly relied upon 'first principles' in both the origination of their concepts and in the detailed development of those concepts. Secondly, all three designers explored the problem space from a particular perspective in order to frame the problem in a way that stimulated and pre-structured the emergence of design concepts. In some cases, this perspective was a personal one that the designers seem to bring to most of their designing. Finally, it appeared from these three examples that creative design solutions arise especially when there is a conflict to be resolved between the designer's own high-level problem goals (their personal commitment) and the criteria for an acceptable solution established by client or other requirements. The outstanding designers are able to draw upon a high-level, or more systemic view of the problematic in which their actions are situated.

These cognitive strategies identified by Cross overlap significantly with those features of expertise in design identified by Lawson (2004) as the reliance upon guiding principles, the ability to 'recognise' situations in a seemingly intuitive way, and the possession of a repertoire of 'tricks' or design gambits. Working at the highest levels of performance in design, outstanding designers aim to produce not just satisfactory solutions, but innovative responses to situations that could – and would – be treated in conventional ways even by ‘expert’ designers. Outstanding designers produce work which goes beyond the solving of the ‘given’ problem. They produce valuable precedent upon which others can come to depend. They generate new gambits which eventually may become standard or common practice.

In pulling our separate studies together, we feel able to conclude that there are enough commonalities in the behaviours of outstanding designers to suggest a view of expertise in design which has its own particular features, with some differences from generic models of expertise which have been mainly drawn from studies in more conventional types of problem solving.

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SESSION SIX

Studying design collaboration in virtual environments
M.L. Maher, Z. Bilda, F. Gul and D. Marchant

An enthographical oriented study of designers in a collaborative design project
S. Joel, M. Smyth & P. Rodgers

Cognitive studies in similarity assessment
J.R. Jupp & J.S. Gero

JS Gero and N Bonnardel (eds), *Studying Designers '05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 291-305

STUDYING DESIGN COLLABORATION IN VIRTUAL ENVIRONMENTS

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Abstract: A design environment could be beneficial either for conceptual phase, detailing phase or modeling phase, however analysis of design behavior is needed for understanding the impact and benefits of the tools/environments. We studied pairs of designers collaborating on three different design tasks of similar complexity using a different setting for each task. This paper presents the analysis of the collaborative design behaviour of one architect pair. The results show that the architects developed abstract concepts, analyzed synthesized and evaluated them when they were involved face to face and remote sketching while the same architects focused on synthesis of the objects and the making of the design, when they were involved in 3D modeling via the extended virtual world.

1. Studying Team Collaboration

The comparison presented in this paper is part of a larger study funded by the CRC for Construction Innovation in Australia[1]. The project includes three streams:

1. The experimental study of designers using different virtual environments to highlight the impact of high bandwidth communication on design practice.
2. The development of a prototype virtual environment that supports synchronous design sessions in a 3D virtual world among designers from different disciplines.
3. The study of the generic skills needed by virtual teams.

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[1] <http://www.construction-innovation.info>

Recent developments in networked 3D virtual worlds and the proliferation of high bandwidth communications technology have the potential to transform the nature of distance collaboration in professional design. There have been numerous developments in systems that support collaboration that have resulted in system architectures to support information sharing and remote communication. Whilst these initiatives have led to important advances in the enabling technologies required to support changes in global economic practices, there remains a gap in our understanding of the impact of the technologies on the working practices of the people who are the primary users of such systems.

Research into the characteristics of collaborative work can assist in our understanding of how the collaborative design process can be supported and how new technologies can be introduced into the workplace. An understanding of collaborative design includes such factors as the role that communication media play, the use of physical materials and computer tools, and the way people communicate verbally and non verbally (Munkvold 2003). Protocol analysis has been accepted as a prevailing research technique allowing elucidation of design processes in designing (Cross et al. 1996). And whilst the earlier studies dealt mainly with protocols' verbal aspects (Akin 1986), later studies acknowledge the importance of design drawing (Akin and Lin 1995), associating it with design thinking which can be interpreted through verbal descriptions (Suwa and Tversky 1997; Suwa et al. 1998; Stempfle and Schaub 2002). By gathering information about the rich and complex picture of collaborative design we can understand the characteristics and needs of the practitioners as well as the factors which contribute to their professional effectiveness.

In studying the impact of high bandwidth environments on design collaboration, an experimental study with 3 design settings was developed:

1. A collaborative design process in which designers work face to face with their current design and communication tools.
2. A collaborative design process in which designers use a shared drawing system with synchronous voice and video conference.
3. A collaborative design process in which a 3D virtual world is used in addition synchronous voice and video conference.

2. Experiment

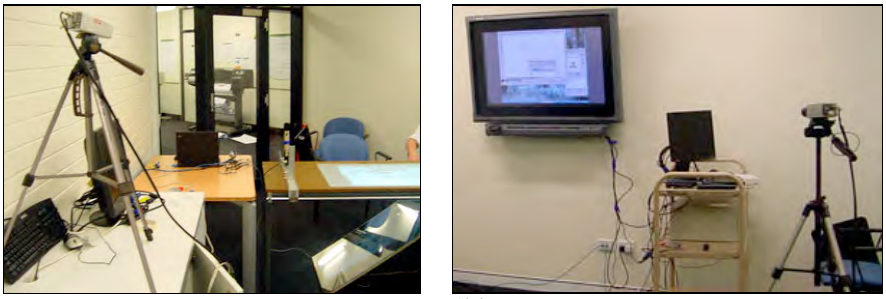
In our experiment, we studied pairs of designers collaborating on three different design tasks of similar complexity using a different setting for each task. We anticipate that the comparison of the same designers in three different environments would provide a better indication of the impact of the environment than using different designers and the same design task. Our designers are architects, so the design task is the design of a small building on a given site. We used the same site for each task, but specified a different type of building (gallery, library, and hostel) for each design task. This allowed the designers to become familiar with the site and to focus on the design of the building.

2.1. EXPERIMENTAL SET UP

Figure 1 shows the face to face session of the experiment where the designers are provided drawing materials (pen –paper), brief and a collage of the photos showing the existing building on the site and the neighboring buildings.

Figure 1 Face to face session

Figure 2 shows the set-up for the shared drawing board environment. In order to simulate high bandwidth audio and video, both designers are in the same room and can talk to each other, but can only see each other via a web cam. The set up for designer 1 is shown in Figure 1a and the set up for designer 2 is shown in Figure 1b. The location of the cameras was an important issue, since we wanted to monitor the designers' movements, verbalizations, gestures and drawing actions. Cameras 1 and 2 capture the gestures, general actions such as walking, looking at, moving to the side, while the direct connections to the computers/screens capture the drawing process. In this setting of the experiment, the designers used Group Board, as shown in Figure 3. One designer used a pen interface (Mimio) on a projection table, shown in Figure 2a. The other designer used a pen interface on a Smart Board, shown in Figure 2b.



(a) (b)

Figure 2. (a) Camera 1, Desktop screen 1, and Mimio on workbench; (b) Camera 2, desktop screen 2, and Smart Board

In the third setting of the experiment, the designers used an extended 3D virtual world application in Active Worlds, shown in Figure 4. The 3D world includes a multi-user 3D building environment, video contact, a shared whiteboard, and an object viewer/insert feature. Again, the designers are in the same room with a similar camera set up. While the shared whiteboard was available in the third setting, the designers were only trained to use the 3D world and the web cam.

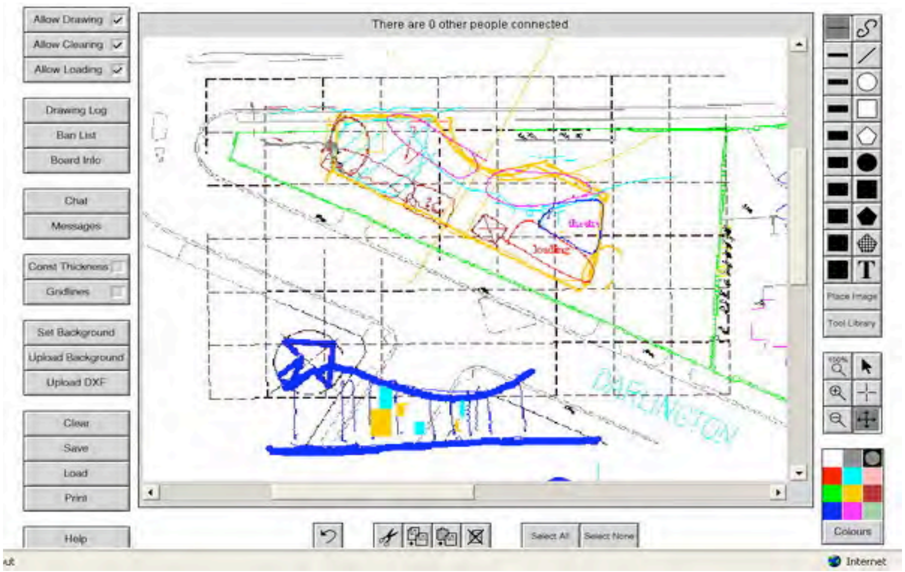


Figure 2. Group Board interface

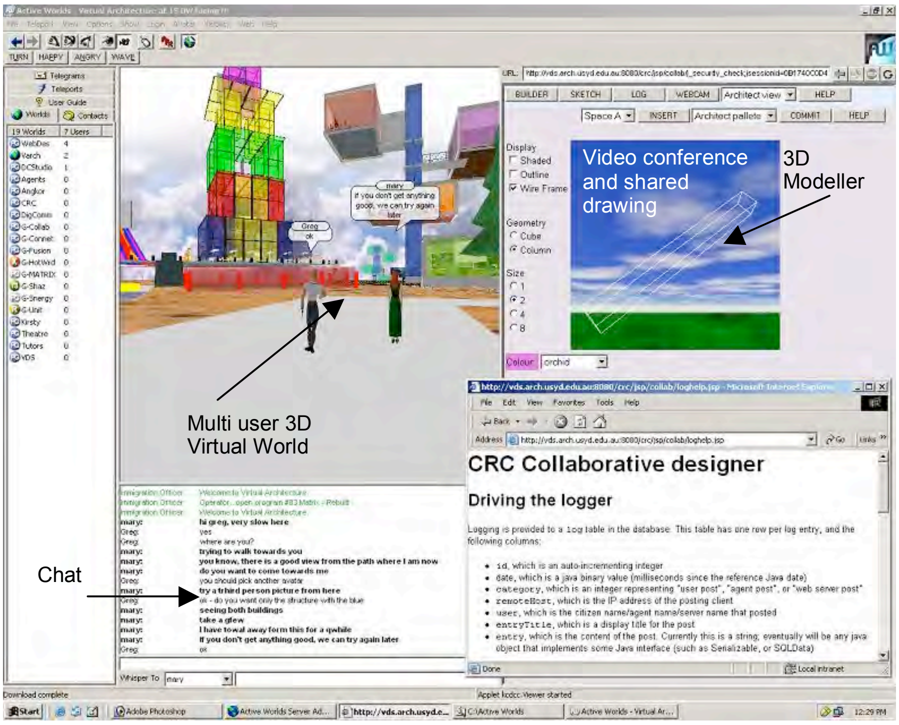


Figure 3. Extended virtual world

2.2. EXPERIMENTAL PROCEDURE

The experimental procedure was:

1. The designers were given a design brief and shown a collage of the photos of the site they are required to build on. They were given time to read through the design brief and inspect the site layout and photos. They were given paper and pencils and were asked to complete their design session in 30 minutes.
2. The designers were presented a short description of how they could use Smart Board or Mimio Tool. These are both pen and digital ink interfaces to a standard windows environment. The Smart Board is attached to a vertical plasma display and the Mimio is placed on a horizontal projection display.
3. The designers were given a 15 minute training session on the use of Group Board. In the training session participants were engaged in doing a tutorial in order to review and/or build their skills in using specific features of the software application provided for collaboration.
4. The designers were given a new design brief and shown a collage of the photos of the same site. They were given time to read through the design brief and inspect the site layout and photos. The site layout was set in the

share whiteboard application as a background image on several pages so that the designers can sketch on them. They were asked to complete their design session in 30 minutes.

5. After a 5 minute break, the designers were given a 15 minute training session on the use of 3D world. They were asked to do a tutorial in order to review and/or build their skills in using specific features of the software application.

6. The designers were given a new design brief and shown a collage of the photos of the same site. They were given time to read through the design brief and inspect the site layout and photos. This time the designers were using the extended virtual world. They were asked to complete their design session in 30 minutes.

3. Analysis of Data

The data from the experiments comprises 4 continuous streams of video and audio data for each pair of designers. In this paper we report on the analysis and interpretation of one of the pairs. The stream of data for each session is segmented for coding and analysis. We used a software called INTERACT[2] for our coding and analysis process; more information on the reasons for choosing this software and how it improved our coding process can be found in Candy et al (2004).

Each segment is coded according to a mapping from the activities and utterances to a set of coding schemes. Our segmentation is based on an interpretation of an event. In the study done by Dwarakanath and Blessing (1996), an event was defined as a time interval which begins when a new portion of information is mentioned or discussed, and ends when another new portion of information is raised. This event definition is an optimal one for our study as well, since the occurrences of actions and intentions change spontaneously as architects draw and communicate interactively.

An event can change when a different person starts speaking in a collaborative activity if s/he is introducing a new portion of information. In some cases the conversation goes on between the actors however the intention or subject of interest remains the same. In this paper we refer to the designers as Alex and Casey. For example, in Segment 48 both Casey and Alex take turns in one segment, however their subject of interest is still the "ramp to a car park":

Segment 48:

"Casey: This is... there is a photo of there. That is actually a ramp to a car park. And then there is a building and a little <inaudible>

Alex: And that is the ramp?

---

[2] www.mangold.de

Casey: That is the ramp."

Then this conversation could be put into one segment despite the change in speaker. Table 1 shows the segmentation of a protocol excerpt from the study.

TABLE 1 Segmentation in terms of event definitions

Segment 11	Casey: You were feeding, the lobbies there but not facing the void. You saw the void from around this way. Alex: Yeah but this is again Site Specific it is related to the <inaudible>
Segment 12	Alex: That is ok. I mean again within that model... Just keep that. I guess the point is
Segment 13	Alex: I think even in this model you can still to have a lift opening up this way or a lift going this way. But what he was suggesting was maybe if we pulled the lifts out
Segment 14	Alex: but I think you could actually put the lifts here.
Segment 15	Casey: You know this... what I am saying... do that, you face this way and you come out and you turn a corner and that is hanging off the edge of the void there is a void there so this is like you come out, like when you are waiting for the lift you come out and you are off the edge.
Segment 16	Alex: I like that with glass under that... you walk past the sort of lobby as you come in Casey: and as you go up this thing jumps out.... Alex: yeah so you could put that line there...

Each segment is then coded according to a coding scheme. The coding scheme allows us to compare and measure the differences in the three design sessions. We used 5 categories of coding schemes: communication content, working modes, Function-Structure, design process, and operations on external representations.

The communication content category partitions each session according to the content of the designers' conversation, focusing on the differences in the amount of conversation devoted to discussing design development when compared to other topics. The working modes category characterizes each segment according to whether the designers were working on the same part of the design, or working separately. The Function-Structure category classes the content of each segment as a reference to the function of the design or the structure of the design. The design process category characterizes the different kinds of designing tasks that dominate in the two different design environments. The operations on external representation category looks specifically at how the designers interacted with their external representation of the design to see if using 2D entities or 3D objects was significant. Examples of some of the coding categories are given below.

Communication Content:

The communication content category is applied to the transcribed conversation between the two designers, and one code is assigned to each segment. This code category has 5 codes as shown in Table 2.

TABLE 2 Communication Content

Software features	Software/ application features or how to use that feature
Design Process	Conversations on concept development, design exploration, analysis-synthesis-evaluation.
Awareness	Awareness of presence or actions of the other
Context free	Conversations not related to the task
Tech Prob	Talking about a technical problem

Communication on software features involves the questions about how to do specific tasks with the software, talking about individual experience of how to do things, problems faced during the use of the software, any feedback about the interface or use of software /statements of frustration about not getting something right etc.

Communication on design process involves statements about design issues, environmental or structural issues, design ideas, design solutions, judgments about design solutions, functional issues or design constraints, client requirements, comments on design brief, in other words any conversation about the design process.

Communication on awareness refers to conversations on participants' presence and actions in a digital environment, for example:

"I see where you are, I'll come down and join you and here I'm".

"aaaha you re working on the NE corner…."

"Did you manage to put walls?

Yes there are a couple of panels at the southwest corner".

Context free communication refers to the conversations that are not related to the design, the software, or awareness of others, for example "shall we have a beer after this?".

Communication on technical problems is coded separately from software features because they are problems that may be resolved in future experiments. The technical problems include software crashes, computer hardware or server failures, internet disconnection.

Design Process:

The design process category characterizes the kinds of design tasks the designers are engaged in for each segment. Assigning a design process category takes into consideration the words spoken during each segment as well as the actions observed in the videos. The codes in the design process category are an adaptation of the coding scheme developed by Gero and McNeill (1998). The codes in this category are shown in Table 3.

TABLE 3 Designing Process

Propose	Propose a new idea/concept/ design solution
Clarify	Clarify meaning or a design solution, expand on a concept
AnSoln	Analyse a proposed design solution
AnReps	Analyse/ understand a design representation
AnProb	Analyse the problem space
Identify	Identify or describe constraints/ violations
Evaluate	Evaluate a (design) solution
SetUpGoal	Setting up a goal, planning the design actions.
Question	Question / mention a design issue (for eg. how to get this done? In terms of areas we have nothing to scale)

Operations on external representations:

The external representations category looks specifically at the actions the designers perform while using the software. Each segment is interpreted using the video of the designers' behaviour including movements or gestures, and the video stream of the computer display showing how the software was being used. Table 4 shows the codes in the external representations category.

TABLE 4 External Representation

Create	Create a design element
Group	Group elements
Move	Orientate/Rotate/ Move element
Erase	Erase or delete a design element
Inspect	Attending to, referring to the representation

The actions required to construct external representations differ in each media. Thus the definitions of the codes in this category need to be explained for sketching and 3D models, as shown in Table 5.

TABLE 5. Examples of operations on external representations

Code	**Sketching**	**3D World**
Create	Drawing a new entity.	Inserting a design object (wall, column, beam, slab, box) into the environment.
Group	Creating entities next to each other, which form a group.	Duplicate an object next to the previous in one segment duration.
Move	Move action is not frequently used in a shared white board, because designers tend to use it	Designers move around the objects after they are created. This is to align them, change their arrangements or to

	like a sketch paper.	carry them for using in another location.
Erase	Select a drawn entity and delete it	Select a created object and delete it.
Inspect	--Looking at the design brief --Looking at the representation and refer to its parts/aspect --Using hand gestures over the representation --Attending to a visual feature of the representation --Zooming in and out --Scanning	--Looking at the design brief --Looking at the model and refer to a design object. --Using hand gestures over the representation --Attending to a visual feature in the environment --Changing the view point in the environment

Working Modes

The working modes category focuses on how individuals collaborate towards the design product: are they developing a product/solution together or are they doing this alone for a while and then work together again along the time line of designing. Similarly Kvan (2000) defined collaborative designing as a "closely coupled" process or a "loosely coupled" process. In a close coupled process, designers work together on the same artifacts simultaneously while in a loosely coupled process, design participants work with different artifacts at different or same time.

In this category "meeting" code refers to designers working together on the same design/artifact, and "individual" code refers to designers working individually on a different part/aspect of the design.

4. Interpretation and Discussion of Results

Our analysis of the data for communication content is summarized in Figure 5. The analysis shows that the communication content in face to face sketching sessions is predominantly about the design rather than about the tools they are using or where the other person is located. During the face to face (FTF) sessions, we observed that designers were intensively engaged in exploring and creating design concepts interactively while drawing on paper. This is explained by the familiarity of this environment for the designers and the physical access they have to each other. We noticed a similar phenomenon in the remote sketching environment, where the designers primarily talked about the design rather than the software features or the awareness of actions of each other. However, in the 3D virtual world we found that much of the conversation was about awareness of other designer's location and action. The discussion on awareness of others is due to the significance of the information about the other designer's location in the 3D virtual world and their actions with respect to the design model they are creating. In a 2D sketch, both designers have the same view. In a 3D world, the view of the designer depends on his location in the world. However, in all 3 sessions, the designers spent most of the communication time on design tasks.

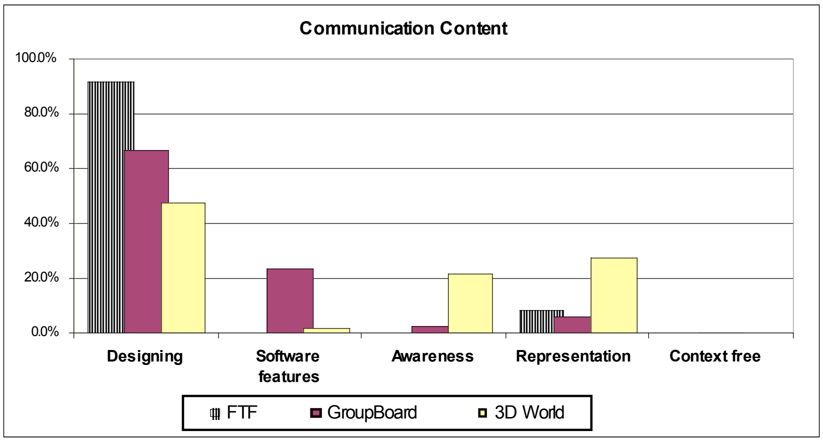


Figure 5. Analysis of communication content

A summary of our analysis of the working modes category is shown in Figure 6. When the designers were working face to face, they were always engaged in "meeting" mode, during which they were communicating and acting on the same aspect of the design. When the designers were working remotely, there was a small percentage of the time during which they were working on their own, focusing on different aspects of the design. We have observed that this percentage can vary greatly from one design pair to another. In the design pair we are reporting on in this paper, the percentage of individual working mode is similar for remote sketching and remote 3D virtual world. An interesting interpretation of these results is that while working remotely, the presence of the other designer is not as strong, allowing the designers to think privately for a portion of the time.

A summary of our analysis of the amount of time the designers spent attending to function vs structure is shown in Figure 7. In the face to face session the designers spent an almost equal amount of time on the considerations of function as structure. In the remote sessions the designers spent significantly more time on structural considerations than on functional considerations.

The analysis of the operations on external representations is shown in Figure 8. This analysis is interesting because the three sessions look very similar. The operations of inspection on the brief and the representation of the design dominated, with the other operations being comparatively small in percentage of time.

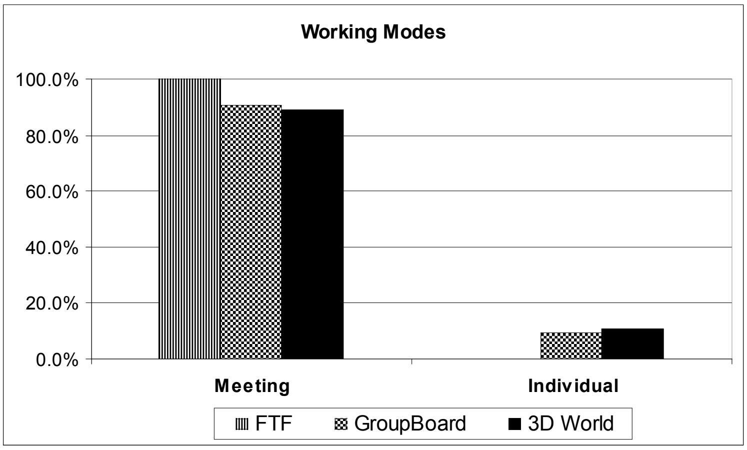


Figure 6. Analysis of working modes

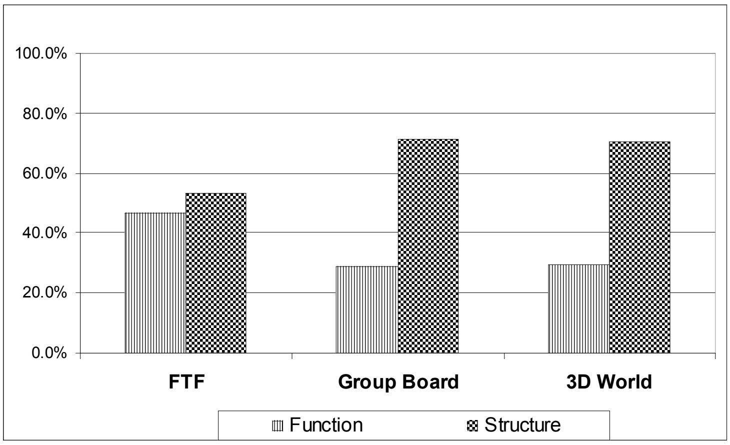


Figure 7. Analysis of function and structure categories

For the design process codes we show the results for each design process code along a time line, as shown in Figure 9. The beginning of the session is on the left, and the length of each segment indicates how long the designer spent on each design task. Each code is applied separately for each designer, indicated by the numbers 1 and 2. From the analysis, we see that the two sketching sessions have similar patterns in the design tasks and the 3D virtual world looks very different. In the sketching sessions the designers cycled many times through a pattern of analysis followed by a pattern of propose. In the 3D virtual world the designers spent the initial time analyzing the problem and then spent a major portion of the remaining time setting up goals. The propose tasks in the sketching environments were usually associated with talking about ideas and sketching.

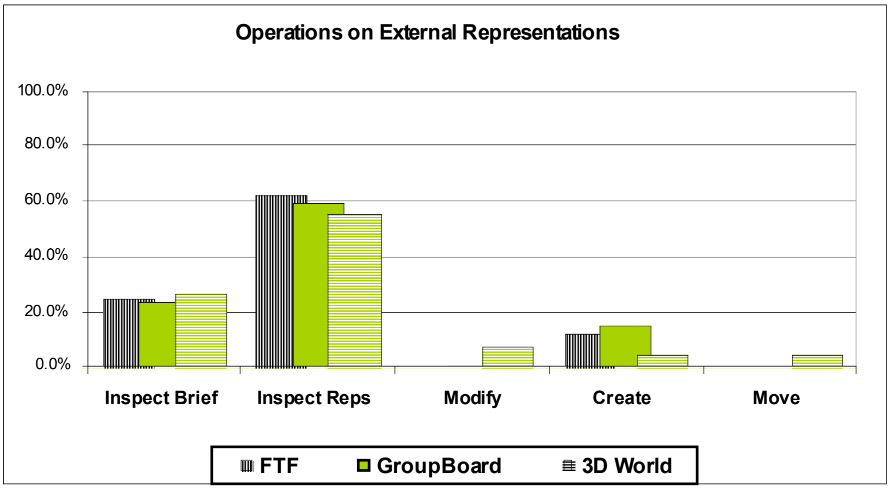


Figure 8. Analysis of operations on external representations

The set up goal tasks in the 3D virtual world were associated with talking about and creating 3D models to build a portion of the design. These differences follow from the differences inherent in the expressiveness of the entities drawn in a sketch and the expressiveness of the 3D objects in the virtual world model. The entities in a sketch can take on many meanings that may be associated with the structure of the design, or not. The 3D objects in a world model can only be associated with an aspect of the structure of the design.

5. Conclusions

Introducing new tools to the design process requires understanding of what purpose they serve. A design environment could be beneficial either for conceptual phase, detailing phase or modeling phase, however analysis of design behavior is needed for understanding the impact and benefits of the tools/environments. The experiments described here characterize and compare the design behavior of two architects using three different tools/media for designing. We demonstrated architects developed abstract concepts, analyzed synthesized and evaluated them when they were involved sketching and the same architects focused on synthesis of the objects and the making of the design, when they were involved in 3D modeling via the extended virtual world.

In this paper the nature and benefits of the three design environments are revealed by analyzing the design behavior of a pair of designers. The results show that the designers' behavior was different when they were engaged in sketching and when they were engaged in 3D modeling. In the 3D virtual world they focused on the details of how objects come together and are synthesized. In the sketching environments they are engaged in the design process on an abstract level i.e. through design exploration.

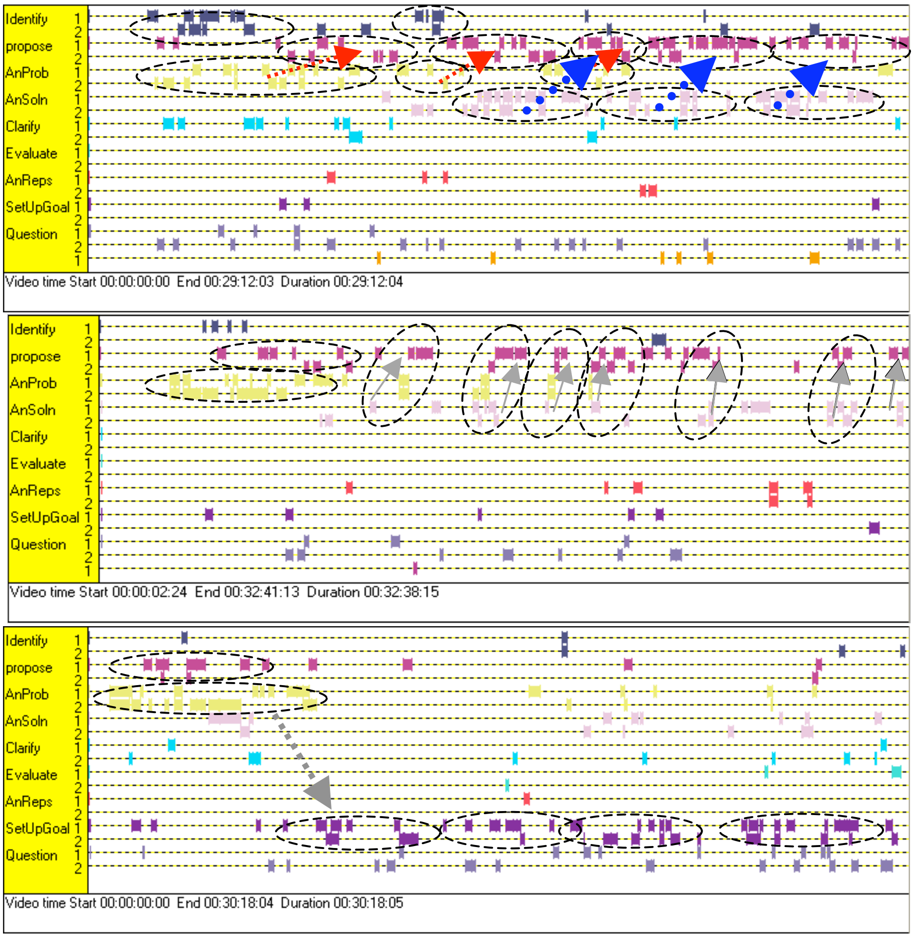


Figure 9. Design process in FTF, Group Board and 3D virtual world sessions

We are currently analyzing the remaining pairs of designers in this 3 phase study, and will begin collecting data on pairs of designers that have both sketching and a 3D virtual world available while designing remotely.

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AN ETHNOGRAPHICALLY ORIENTATED STUDY OF DESIGNERS IN A COLLABORATIVE DESIGN PROJECT

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Abstract. This paper discusses a six-week ethnographically orientated study of the social influences involved in a collaborative team project. This paper describes the methodology used, the implications such a theoretical basis can have on the research undertaken, and how the research was carried out in practice. Finally, the paper looks at the initial findings and the social influences at work during the design project. It is envisaged that during the design process, particularly in an inter-disciplinary teamwork situation, there are many complex social domains that can both constrain and foster creativity.

1. Introduction

This paper reports on a six-week study carried out during February and March 2005. The study forms part of ongoing doctoral research into collaborative design projects and in particular how teamwork and social groupings influence designers. To understand the six-week study at Napier University, a brief introduction is given to the research in general to place the study in context. The research aims to analyze and question the social world of designers, and how this social world can influence, inspire or hinder the design process. Designers can be seen as forming certain behavioral patters of interaction (Bruce 2005). They work with certain people, and socially mix with a certain group of friends. How do these social networks, therefore, affect their work? Designers also exhibit different behavioral patterns throughout the design process (Zurlo 2005). What is the effect of these emergent pattern trends?

The ethnographically orientated study can be seen as the first step toward analysis of these social networks. The participant observation enables a first hand view of how designers (albeit student designers) interact with people and the influence this can have. The Napier study particularly looks at the inter-disciplinary team, who notably haven't met before. The study particularly looks at what aspect this can bring to the social interaction equation.

There has been much discussion about the use of team working in the design process. Teamwork and social processes have been proposed as significantly interacting with the technical and cognitive design processes (Cross and Clayburn-Cross 1995). Designers, particularly student designers, are increasingly asked to work with persons of different disciplines, and this has been perceived as bringing a positive effect on achievement (Springer, Stanne and Donovan 1999). However others have argued “there are almost no differences between the individual and the team in the way they bring their work to fruition” (Goldschmidt 1995).

In terms of academic design courses, teamwork situations are increasingly constructed. Students are asked to work in cross-disciplinary groups to simulate “real world” practice. Furthermore, students are expected to present and articulate their own field of expertise, as well as draw on the input they receive from persons outside their own discipline.

2. The project

The research described in this paper is based on a project that was part of two academic courses being run at Napier University, Edinburgh, Scotland. The six-week project required undergraduate design students and masters level multimedia students to produce a concept and software prototype for an interactive installation for the Wembley Stadium[1] museum. The students were organized into groups of four with two members of the group being from the design course (students **F** and **C**) and two from the multimedia course (students **M** and **J**). The group of four team members consisted of a male/female pairing from each course. Three of the four students were Scottish and one was from Northern Ireland. The students ranged in age from 19 to 32. To complete their relative modules, the undergraduate students needed to produce four presentation boards that conveyed their team’s concept. The graduate students were required to produce a software prototype using that concept. The project brief was stated as:

“*Design an interactive installation for the Wembley Museum. Your concept will celebrate Wembley’s rich and diverse history and present the new Wembley as an iconic landmark to inspire the next generation of fans and host the world’s greatest*

[1] Located in London, Great Britain, Wembley Stadium has a long and glorious history, not only for sporting achievements but also as a music venue. It has hosted Football Association (FA) cup finals, the live aid concert, and world cups for both rugby league and football. Struggling to meet public demand, the old stadium was closed in 2000 to be replaced by a larger capacity venue. The new Wembley Stadium, with 90,000 seats, will be the largest arena in Britain and the largest under-cover football stadium in the world.

players. This interactive experience should juxtapose a glorious heritage with the venue's future potential in a unique and engaging form."[2]

The Wembley Stadium museum aims to capture past glories held in the old stadium while looking to the new stadium for future triumphs[3]. It is in this context that the students embarked on their coursework.

3. Methodology

An ethnographically orientated methodology was adopted for the study. Ethnography can be summarized as, "the study of people in naturally occurring settings", "involving the researcher participating directly in the setting", "in order to collect data", "without meaning being imposed externally" (Brewer 2000). Its use was chosen as it enables a holistic view of the design process. It is also particularly apt at understanding the varying types of complex social interactions that are at work in a student design course (Ashton and Durling 2000).

The ethnographic approach in practice involved the presence of a researcher for the full duration of the design project. The researcher targeted the times when all four members of the team were together and collaborating. During the study, notes, recordings, photos and Dictaphone interviews were taken. A breakdown of what equipment was used and when is detailed in Table 1. To analyze conversations, observations and general notes, a qualitative software tool[4] was used. The software helped enable the raw data to be sorted, to show the number of interactions made by each participant and importantly to codify certain excerpts.

The reality of the ethnographic research outlined in Table 1 was that the various techniques used ranged in quality and value. In some locations, when cafes were chosen as an informal meeting place, it was difficult to hear some of the conversations because of background noise. On other occasions, some equipment was inappropriate. For example larger cameras were generally avoided in cafes or public areas, as they were conspicuous. However these considerations are all part of the process involved in participant observation in real-world settings.

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2 http://www.dandad.org/education/studentawards/pdf/Interactive_SACFE2005.pdf

3 www.wembleystadium.com

4 http://www.qsr.com.au/

TABLE 1. Breakdown of study

Session(s)	Date	Purpose	Equipment
1	10 February	Introductory Session	-Digital Camera (still)[5] -Notes
2	15 February	Precedence analysis	-Notes
3	17 February	Formal seminar	-Digital Camera (video)[6] -Notes
4 to 7	17,21,23,28 February	Informal meeting	-Digital Camera (still) -Digital Camera (video) -Notes -Dictaphone[7]
8	1 March	Formal seminar	-Dictaphone -Notes
9	3 March	Studio session	-Digital Camera (video) -Notes
10 to 11	8,10 March	Formal seminar	-Digital Camera (video) -Notes
12 to 13	14 March	Informal meeting	-Digital Camera (video) -Notes
14	17 March	Final Presentation	-Digital Camera (video) -Notes
15 to 16	17 March	Informal meeting	-Digital Camera (video) -Notes

Although on balance, an ethnographic approach seems appropriate, it should be noted that an ethnographic technique brings with it some inherent research issues that have influenced the final interpretation of the six-week study. The presence of only one researcher during the project, results in the data being very much based on the individual researcher's pre-conceptions. The findings and video editing process are thus liable to be biased. It may also be the case that the actions and behavior of the students could have been effected by the presence of the researcher and camera. The analysis also does not fit neatly into the six-week study period. Since the project finished the researcher has often spoken to the students in cafes and lab rooms. The

[5] Panasonic Digital Camera DMC-FZ20

[6] JVC Digital Camera (GR-DVP7E)

[7] Sony Dictaphone IC Recorder

conversation regularly turns to the subject of the project and general reflections are quite often made.

4. The ethnographic story

When reflecting on an ethnographically orientated study, the passage of time in which the Wembley project took place can be seen as a series of instances, which link together to form a story. In terms of the Wembley project, there is a clear demarcation of beginning, middle and end. Although in terms of an ethnographic study, this ending point is somewhat more difficult to define. The ethnographic researcher enters the project at its very start and allows a fresh introduction to the subject and the participants. Photos from the introductory session are shown in Figures 1, 2 and 3. Throughout the bulk of the project, there were "excerpt based commentary units" (Emerson 1995: 194) which can be re-told chronologically, through references to the design process, or, as in the case of this paper, specific themes identified. The initial findings sections of this paper are organized into these themes. The ethnographic story also, of course, has an ending. The result of the project could be described for example. However in this instance, there is a reflection on the study as a whole, summarizing the general feelings and conclusions in hindsight.


Figures 1 and 2: Design students constructing the map of the world

Figure 3: Both MSc and Bdes students standing on the world

To begin this ethnographic account, an arrival story:

"The B22 design studio was the setting for my first introduction to the project. The studio was empty when I first entered it, and the desks and chairs were arranged around the room, rather than in regimental rows. The room was also filled with work from previous projects. There were models and posters from previous years that dominated room corners and cupboards. There were also bits of card and material strewn around desks and shelving. It was in this setting that I was told about the Wembley project brief, the D&AD awards and the course in general.

My introduction to the students was in the same B22 design studio. This was the first formal studio time for the Wembley project. When I arrived in the room the students were already busy working. They had been given the task of creating a visual map of the world, which should take up the size of the room. The strewn material that had seemed so messy previously was now being used to make models of the Rocky Mountains and Great Wall of China.[8]"

[8] Continuation of arrival story… "Pre-dominantly British in origin, it struck me how extrovert the Bdes students seemed as a group. They freely moved around and chatted with each other. They were friendly to me as well and while I set up my camera, they asked me questions and were inquisitive.

The purpose of the virtual world was to facilitate conversation between the MSc students and Bdes students and ultimately form groups for the rest of the project. The MSc students hadn't created the models and were exposed to the map and the Bdes students at the end of the studio session. When the MSc students arrived they seemed a little hesitant. The newness of the studio, the course and large map of the world, seem a little puzzling to them. All students were asked to stand on the map on a place where they had visited or wanted to visit. The students initially shuffled round nervously but then got into the idea. The room was very full and some areas of the map were very popular. The room bustled with conversation about where people had gone on holiday. I tried to make my way round the room but there were so many people that I become trapped in the Japanese corner."

5. Initial findings

5.1. COLLABORATIVE INPUT

The following findings relate to observations and video recordings as outlined in Table 1. Themes and conclusions that have arisen are referenced against when supporting evidence occurred during the study. This evidence has the corresponding Table 1 session index numbers.

5.1.1. Course peers

The students under observation received influence from their course peers. Course students could view and analyze each other's work as well as provide verbal feedback. The precedence analysis session (Table 1: Session 2), for example, consisted of students presenting their research to the course as a whole. The course students commented on and noted this work. They also regularly referred to their course-mates research, particularly that shown in the precedence analysis session. The following excerpt is taken from an informal meeting with all four team members (Table 1: Session 4) and refers to a website shown during the precedence analysis.

*Student **F:** Like what was that thing like that student N…*
*Student **C:** That was amazing, I don't know. We'll try and get the website. It was an introduction to a design company on a website and it was like a film, it's just…*
*Student **F:** It was like a trailer*
*Student **C:** For a film and everything happening*
*Student **F:** It was like surround-sound like this [student wildly moves his hands around]*
*Student **C:** Coming from these two little speakers*
*Student **F:** It's on a website yeah. I'll try and get it. I can text it*

The participating design students often asked other students for their opinion on their work. Some of their work can be seen in figure 4. The following excerpt is taken from the studio session shown in figure 5 (Table 1: Session 9).

*Student **F:** A day in the game, but what do you think it is if I say 'a day in the game'*
[Another course student replies but the audio is not picked up on the camera]
*Student **F:** Yeah that's it*
*Student **C:** It's a league table*
[The other course student out of shot from the camera]: I kind of had an idea
*Student **F:** I know, should I ask someone else? But I mean, I think with the visuals though. You know like by saying 'a day in the game' you're going to be in the game.*

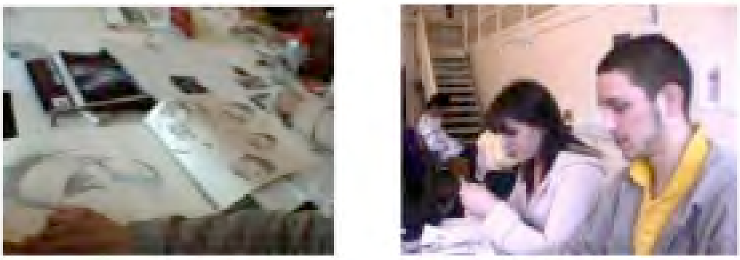

Figure 4 and 5: Design students working in the studi*o*

The students judged their work against their course mates. The following comment is made in a computer center [Table 1: Session 9].

*Student **C:** I bet student J and student F, I mean student A's are amazing.*

The insinuation is that because student **J** and **A** both know a lot about the subject matter, namely football, their work will somehow be superior. The comment is made after a long discussion between student **F** and **C**, in which they talk about not knowing the subject of football.

The students under observation had a strong relationship with their other classmates, often meeting with them socially during evenings and weekends. Cliques within the courses were identifiable and the participant students went to lunch with the same sub-group of people.

The participant team, as a whole, compared their work to other teams and this can be seen as a more complex influence. There were discussions about personalities from one course and the influence they had on the other course and other team in general. The following is taken from one informal meeting with all four team members (Table 1: Session 4)

*Student **J:** Do you remember student L saying he though he was meeting his students*
*Student **M:** I just walked past on the way back from having coffee and there are two design students so obviously one of our group didn't even turn up.*
*Student **F:** That's the thing we were only told yesterday*
*Student **J:** Because our lot didn't know, student L didn't know that he was meeting his ones*
*Student **F:** One of our groups got told by one of their girls that today doesn't fit in with their timetable so she won't be able to make it in time.*

5.1.2. Tutors

The course tutors had an influential effect upon the participant students and their work. Each week the student's work in progress was critiqued. A critique session is shown in figure 6.

Figure 6: The team participating in a critique session

The work of the students was directly affected by these tutorial seminars. For example, the first tutorial seminar had all four students present with one of the design tutors (Table 1: Session 3). The tutor advised the students that a certain approach they were considering (augmented reality) might be difficult. The following excerpt is taken from that seminar:

Student ***M:*** *Ours is Future Media. So we started looking at stuff we can use for the future. We found a thing called Augmented Reality. [print outs about augmented reality are handed round]…. If you read through this [the print out] it will give you a brief idea.*
Student ***J:*** *The idea is to mix the real and virtual world. The examples that exist in museums that have show pieces and show cases. You can animate/activate them with this.*
Tutor ***P:*** *What about, um… have you read the brief and then read the brief and then read the brief again? Do you think…*
Student ***M****: What brief? The coursework support?*
Tutor ***P:*** *The brief for the project, for the Wembley stadium. Do you think they're looking for a VR solution or type of solution?*

After the seminar, the students had an informal meeting (Table 1: Session 4). The design students, those directly assessed by the seminar tutor, would not consider the augmented reality suggestion even though they personally expressed an interest in the idea. The following excerpt is taken from a follow up informal meeting later in the project (Table 1: Session 5):

Student ***M:*** *Did you read up on AR?*
Student ***C:*** *Yes I did*
Student ***M:*** *Did you read up on the stuff [student M shakes his head], tut, tut. They*

wouldn't even do one thing for us.
Student ***C:*** *The notes that you gave student F? I think it is good but I still… we should look at other things.*
Student ***M:*** *I think tutor P scared you off*
[student C nods her head]
Student ***C:*** *I believe if my tutor tells me it, I'm going to go with it as they're the ones who are marking it.*

To resolve issues, the students used the course tutors. In the studio session (Table 1: Session 9), for instance, the design students **F** and **C** discussed whether or not to include some photos. One student thought they should be included, the other thought they shouldn't. The following excerpt is taken from that session:

Student ***C:*** *Yeah, I just didn't like the pictures*
Student ***F:*** *We'll agree to disagree at the moment*
Student ***C:*** *Yeah*
Researcher ***S:*** *What do you do when you have conflicting, well not conflicting but…*
[laughter]
Student ***C:*** *We compromise*
Student ***F:*** *Yeah but we try and work it out, but I'm just not prepared to give in at the moment*
[laughter]
Student ***F:*** *I think when we say to tutor P or something*
Student ***C:*** *Yeah*
Student ***F:*** *But my ideas are generally better*
[laugher]

Indeed in the following formal seminar (Table 1: Session 10) the issue arose and the question put to one of the tutors. The following excerpt is taken from that session:

Student ***F:*** *Yeah I like that, but student C doesn't. I'd quite like to do a group photo so they can see themselves next to their team name.*
Tutor ***I:*** *Maybe, maybe not. How do you find out whether that's going to work or not for this project?*
Student ***C:*** *Some people may not like having their face plastered on a big screen.*
Student ***F:*** *Yeah*
Tutor ***I:*** *That's an argument. How do you find out whether that's true?*
Student ***C:*** *By asking people*
[Tutor I nods]

5.1.3. Family and friends

Friends and family were used for testing concept ideas and presentations. Both design students referred to running their ideas and presentation past their friends and families. The approach was actively encouraged by tutors, and during a formal seminar (Table 1: Session 10), the following comment is made:

*Tutor **I:** I would get these boards when you put them together and get some random punter who will sit and say 'right what's this?'.*

Friends and family also offer sources of knowledge. The following comment is made during a café meeting (Table 1: Session 5):

*Student **C:** I was speaking to my cousin at the weekend and she's a high school teacher and they've got these things now, like blackboards, called smartboards. And basically you can type into a computer and move it around on the screen which is quite simple. So we researched that.*

Family members and friends, external to the course, were used to impart feedback. They provided a "fresh pair of eyes" and would view the work without knowing the project very well. In the studio session (Table 1: Session 9), both design students phoned their friends to ask them questions that directly related to their concept. The following excerpt is from that studio session:

*Student **F:** When you're doing design it's quite good to get other people's opinion. Some people think that design can be quite daft. You know like my mates are always saying 'you look at things from a different point of view'. But they look at things from a different point of view from me. So they say you should do this and it's a brilliant idea*

Similarly, in one informal meeting (Table 1: Session 4), one team member commented that she was going to take her children to a museum to experience some of the interactive installations. One of the comments that student **J** made appears below:

*Student **J:** We'll take them to the science museum on Saturday and we'll see how they find it. They just love places like the discovery center. We'll do that and that will give us some ideas and we need to think about the interface again and we'll look at some websites and see how we can get that interface*

It was clear that the students referenced family members to envisage concepts from different perspectives. Be it, their children, as in the case above or their mothers. The case below refers to wearing a head-mounted display, part of a discussion in one informal meeting (Table 1: Session 4)

*Student **M:** I think it would be very popular*
*Student **J:** There are quite a lot of adults that wouldn't do it*
*Student **C:** My mum wouldn't do it…*
*Student **J:** Older people*
*Student **C:** It would mess up her hair*

5.1.4.The team members

The four group members worked happily together. On one informal meeting (Table 1: Session 12), when only the masters' students were present, it was asked how they thought the project had gone. Amongst other remarks, one of the MSc students commented:

*Student **J:** We've got on really well with the design students, as they're really good students and we really like them.*

The two students from each course were particularly close, as they had worked on previous projects together. For example, references and "in-jokes" about past work were made in one informal meeting (Table 1: Session 12).

*Student **M:** Then I'm going to get into scenario and talk about future developments and what we could have done and then I was thinking we could put in our logo, rocket media productions.*
*[Student **M** and **J** laugh]*
*Researcher **S**: Are you trying to do a spin off company?*
*Student **J**: No, one of our other projects we have to urm…make a dvd from video and we've called ourselves rocket media productions and we've already got a logo.*
*Researcher **S**: Oh right*
*Student **J**: It's a flash logo with a rocket*
*Student **M**: It looks really good*

The student pairs were very relaxed in each other's company and often interacted in friendly banter. This can be seen in the studio session (Table 1: Session 9) and in the informal meetings when only the postgraduate students are present (Table 1: Session 12 and15).

Analysis was carried out on the input each team member contributed to two particular informal meetings. One meeting was held in a meeting room (Table 1: Session 4), the other in a café (Table 1: Session 7). Figure 7 shows the meeting room analysis and figure 8 shows the meeting in the café. These two meetings were chosen because only the four-team members were present for the meeting duration (there was no outside influence from other students or tutors). To achieve the figures below, the number of comments made by each individual were counted. It should be noted that the amount of time spoken per comment, is not reflected. It could easily be the case that a student may speak in-frequently but to a great length. The figures 7 and 8 below also do not reflect the quality of that which was spoken. Some people may speak less but have more influence.

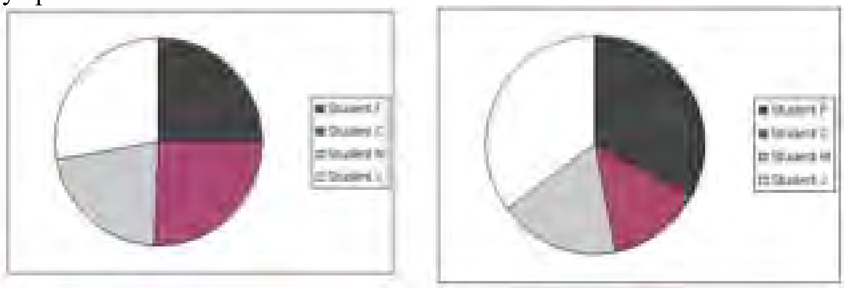

Figure 7 and 8: Student Input (Table1: Session 4) and (Table 1: Session 9)

Interestingly, figure 7 shows that there was almost an equal level of input from all four students. However ten days later in figure 8, there is a shift in input levels, with student **J** and **F** inputting more frequently into the discussion. On reflection, this second trend was generally observed for the rest of the project.

6. Contribution

Fundamentally this work contributes to the academic understanding of designers working in a collaborative team, and how this affects the social influences at work in the design process. In many ways, the study described in this paper repeats research into the design process and design students. Ashton and Durling (2000), for example, looked at social interactions and the effect upon student designers. Similarly Strickfaden et al (2005) looked at the intangible and tangible influences on students. The findings in this paper can be seen as concurring with the outcomes that they put forward. However the Napier study looks at the interdisciplinary teams and the added dynamic this can bring to the social interactions at work. Although the Napier study looks at how four team members interact, this interaction relates to the broader context of social influence.

It should be noted that the Napier study looked at an interdisciplinary team where each pair did not know the other pairing or the other subject discipline. A comparison is not made between a team where all four members are known to one another and from the same discipline, this aspect can be proposed for future work.

The Napier study infers that by the participant students referring, in conversation, to certain social influences, that these influences exist. However the quality, value or effect of these influences is still an open question. These types of questions are difficult to answer, and any possible verification from the Napier study is based on qualitative and anecdotal evidence. Future work therefore, seeks to evaluate the effects of social influence, rather than simply stipulating that complex social influences do exist. Future work also aims to add quantitative evidence to the Napier study by tracking the interactions designers have with one another and applying social network analysis.

The ethnographically orientated study carried out at Napier can be seen as fitting into wider research and broader research aims that contribute more uniquely to the field of studying designers. The ethnographically orientated study informs the understanding of social interactions in an observed qualitative way and begins the process of mapping designers to social networks. Ultimately a holistic approach is envisaged which takes the ethnographic field data, with quantitative social interactions and applies an evaluation mechanism to judge whether certain social configurations constrain or benefit the designer and design process.

7. Conclusion

Collaborative projects, particularly involving persons from different academic backgrounds tend to be very socially complex. The collaborative design project discussed in this paper is shown as having multiple social influences. Each individual team member, for example, brings to the table a network of social factors that have a bearing on the work produced. Figure 9 shows the network of connections between students, their course, tutors and peer group. Interestingly, it can be seen that the MSc students mixed with the friends of their design teammates, but the reserve was not the case.

To conclude this ‘ethnographic story’, a few comments about the research and observations with the benefit of hindsight. Looking back on the Wembley project, the team can be seen as clearly being influenced by each other, their tutors and family and friends. There are obviously many other influences to the design process, however this paper focuses upon only these social references. It is an open question whether the collaborative inter-disciplinary group was more effective in completing their project than an individual designer or a team of designers from the same discipline. Regardless of the creativity or output to the project itself, the benefit from this type of team is that a connection was made between individuals. The following observation is made to illustrate the point.

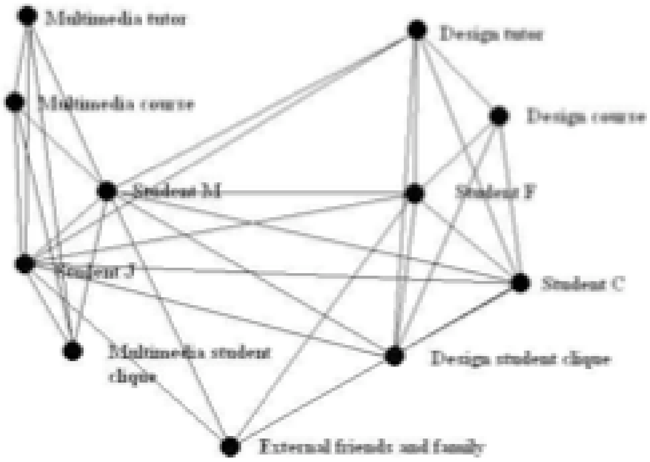

Figure 9: Connections between people and certain groups

"*A few weeks after the project had finished I bumped into student F in the D36 Digital Media Laboratory. I was pretty surprised to see student F as the lab was very much the domain of the MSc Multimedia students. We had a chat about what he'd been up to recently and I asked him what brought him to the Digital Media Lab. He replied that he was editing some video tapes for his new project and the MSc students were helping him with the Final Cut Pro software.*"

The above example shows how the connection made during the Wembley project lasted beyond the scope of the project. Theoretically skills that each team member has could be tapped into for future reference. Each inter-disciplinary team (assuming they worked well together and were friendly) increases the number of social connections an individual team member has. These social connections, therefore, form a resource. Future research aims to show whether that social resource aids creativity and productivity.

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COMPUTATIONAL AND COGNITIVE STUDIES IN SIMILARITY

Evaluating a Neural Network Model of Visuospatial Similarity in Design

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Abstract. In this paper the cognitive plausibility of utilising self-organising maps in similarity assessments of 2D design diagrams is analysed using human-subject experiments which focus on designers. The experiments reported here are designed to address the validity of the computational approach to similarity and investigate feature types, feature salience and the role of context in cognitive assessments.

1. Introduction

This paper presents a cognitive evaluation of a formal model of 2D visuospatial similarity assessment in design and discusses validation aimed at testing the model's utility. In a previous paper (Jupp and Gero 2005) this research presented a computational model of similarity that compares qualitative re-representations of 2D design diagrams. A model of 2D design similarity is only useful if it can provide results that can be recognised or matched by an observer's judgements. Cognitive validation is explored here in studies of intuitive similarity assessments made by designers and compares these judgments against the results of model.

It is expected that the results from cognitive similarity assessments will mirror most of the distinctions made by the computational model, or at least identify correlations and insights into the clusters and ordering of 2D design diagrams made by the model and by designers. It is also expected that studying human-subject similarity assessments will provide some insight into the different types of perceptual grouping strategies as well as the different types of features used during comparison making and their relative salience using different similarity-based assessment methods.

The remainder of this paper is divided into six sections. The approach to similarity assessment is presented in Section 2 in conjunction with a summary of the computational model presented by Jupp and Gero (2005) and the general results obtained. The section also contains a discussion of research in psychological similarity assessment outside the design domain. The experiment design and set-up are described in Section 3. Three experiments are presented using 36 architectural design students from the 1st and 5th years. The results are presented in Section 4 with an analysis that tests five hypotheses. Section 5 discusses these results in relation to other studies of similarity assessment contained in the literature. Section 6 then concludes the paper.

2. Similarity Assessment

The approach to similarity assessment adopted by this research moves away from the idea of similarity as the outcome of a direct comparison procedure and towards the idea of similarity as a process whose outcome can only be the reported in a post-hoc fashion. The neural network approach suggests that similarity is related to the way in which information is processed, where the reporting of similarity is a meta-cognitive process requiring the explicit comparison of information prior and subsequent to processing by the cognitive system (Thomas and Mareschal 2000).

2.1 COMPUTATIONAL SIMILARITY ASSESSMENT

The neural network model of similarity previously proposed (Jupp and Gero 2005), called Q-SOM, is based on a Self-Organising Map (SOM) and a hierarchical feature-based schema for qualitative re-representation of visuospatial attributes. The features derived from the re-representation of 2D design diagrams are capable of describing three levels of spatial information, namely: morphology, topology and mereotopology. The similarity assessments made by the Q-SOM model relies on these features as input to the network. Processing follows four consecutive stages: (i) recognition, extraction and encoding of different levels of spatial attributes; (ii) initial feature selection of spatial attributes; (iii) categorisation via unsupervised learning of 2D diagrams based on available features; and (iv) identification of clusters using K-Means clustering.

Q-SOM was tested on a corpus of 61 plan diagrams from the 20th century architect Frank Lloyd Wright (Jupp 2005). Wright's residential plan designs from 1885 to 1940 were used as the dataset for these experiments. The designs from Wright's corpus are structured (agreed upon by both historians and critiques) into four periods: early, prairie, transition and usonian. From each of the four periods, a fixed ratio of approximately 3.5:1 determined the number of diagrams randomly selected for training, giving a total of 15 diagrams. The training set comprised: 2 early, 6 prairie, 2 transition and 5 usonian diagrams. Networks were trained unsupervised and no explicit contextual information was input. A level of contextual information could be said to be implicit in the feature semantics derived from diagrams. There is no explicit connection with a design context, for example any kind of design scenario or design requirement.

The output of Q-SOM's networks were evaluated statistically using techniques from conventional text-based analysis including: Precision (Slonim et al 2002), the Jacaard method (Downton and Brennon 1980), and the Fowlkes-Mallows method (Fowlkes and Mallows 1983). Based on these internal performance measures it was observed that using multiple classes of features yields better results for classifying diagrams according to the four periods of Wright's work than any one single dimension. Results revealed that using a larger set of features based on a combination of available morphological, topological and mereotopological features yields better results than using a smaller subset of features. For these results to be meaningful to designers, they must now be evaluated in relation to cognitive similarity assessments. Validating the Q-SOM's correspondence to human-subject similarity judgments can be achieved by demonstrating that the outputs of the SOMs are similar to those judged by an observer.

2.2 PSYCHOLOGICAL SIMILARITY ASSESSMENT

Assessing the similarity of objects is neither simple nor well understood (Palmeri and Gauthier 2004). How mental representations of categories work and how they are related to similarity judgements remains a controversial question (Lambert and Shanks 1997, Medin et al 2000, Palmeri and Gauthier 2004). There are four major psychological models of similarity: geometric, featural, alignment-based, and transformational; and all four approaches have enjoyed some success in quantitatively predicting people's similarity assessments. The approach of the Q-SOM model summarised in the previous section, and which is now tested here, is featural.

There is great variability within the literature regarding the types and combinations of techniques used to validate neural networks. Although computational evaluation is widely used to validate the output of neural networks, (e.g. the Precision, and the Jacaard and Fowlkes-Mallows methods) cognitive validation is less prevalent. This is most likely due to the complexities and ambiguities in studying human-subjects since, in general, similarity based assessment may not be a unitary measure and may also depend on representations that are constructed and changed by the designer during comparison-making. Goldstone (1994) enumerates the difficulties in studying similarity assessments, reporting that the explanatory role of similarity may not be a unitary phenomenon. Similarity can be influenced by context, perspective, choice, alternatives, and expertise (Medin et al. 1993, Tversky 1977). Different processes for assessing similarity are probably used for different design tasks, and design diagrams. For example, the similarity of diagrams can be assessed based on its complexity or can be influenced by the design task at hand. Specific features may be selectively weighted during assessments and evidence from previous research indicates that the weighting of features in similarity judgments may also vary dynamically during processing (Goldstone 1994).

In light of the difficulties in studying cognitive similarity assessments, one of our principal concerns in designing experiments lies in studying a variety of methods for similarity assessment and ensuring that the assessments made are intuitive and not guided or constrained by strict definitions. All participants shared a common understanding of the concept of similarity and the type of perceptual information being assessed. The following section describes the experiment design.

3. Experiment Design

The main objective of the cognitive experiments is to evaluate the correspondence between the subjects themselves and between subjects and the Q-SOM's output rather than the four periods defined by historians and critiques which partition Wright's designs into some kind of category or style. Wright's periods are defined as the 'correct' classification and the evaluation of results are based on these characterisations.

The experiment consisted of three questions. The same 15 diagrams used to train the Q-SOMs networks (Section 2.1) were again utilised as this study's design corpus. As in the computational experiments, the selection of Wright's residential work includes diagrams from the early, prairie, transition and usonian periods.

3.1 SUBJECTS

Participants were recruited from the 1st and 5th (final) years of the Bachelor of Design Architecture degree at Sydney University. The 36 participants were all unpaid volunteers. Subjects' ages ranged from 18 to 32 years. The 36 subjects included 21 females and 15 males. For approximately 75% of students English is their first language and the remaining 25% of students were fluent in English. Subjects responded to each question at the same time, i.e., in group sessions, and were allocated the same amount of time to provide their answers.

3.2 SET-UP

The selection of 15 plan diagrams is illustrated in Figure 1 and Table 1 lists corresponding label and period, where E = early, P = prairie, T = transition and U = usonian.

The general method of the experiments enabled participants to study and then rank the corpus. Before subjects undertook each experiment, a training session was provided to familiarise designers with the task. During this training period general definitions and guidelines were described, including: the concepts of physicality, and similarity. In addition, illustrations of diagrams were controlled using strict criteria.

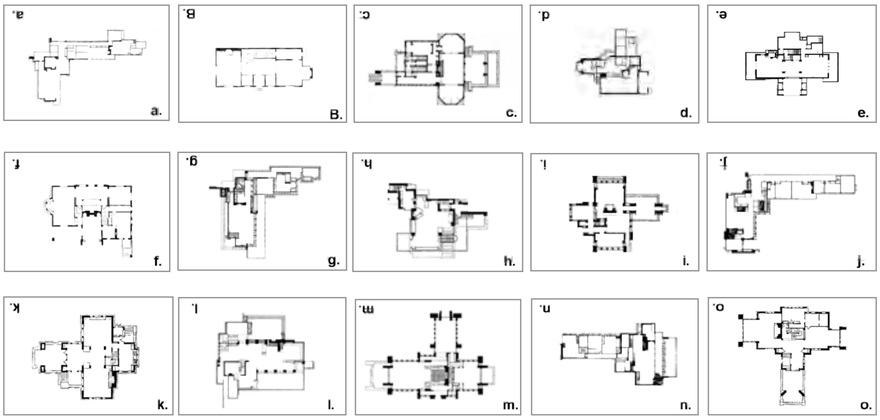

Figure 1. Selection of 15 plan diagrams for the design corpus of Frank Lloyd Wright

TABLE 1.Correct partitioning and ordering of diagrams based on Wright's periods.

LABEL	b	f	c	k	i	o	e	m	d	h	g	j	a	n	l
DIAGRAM	CHARNLEY HOUSE 1891	WINSLOW HOUSE 1898	HENDERSON HOUSE 1901	BARTON HOUSE 1903	COMM. HOUSE 1903	LITTLE HOUSE 1903	DERHODES 1906	ULLMAN (UNBUILT)	YOUNG HOUSE 1929	KAUFMANN HOUSE 1935	JACOBS HOUSE 1936	LUCK HOUSE 1936	GARRISON HOUSE 1939	NEWMAN 1939	SCHWARTZ HOUSE 1939
PERIOD	E	E	P	P	P	P	P	P	T	T	U	U	U	U	U
TOTAL Nº.	2		6						2		5				

3.2.1 Understanding of Physical Comparison

Subjects were instructed to base assessment on a diagram's physicality and asked to identify similarities based only on visuospatial information. Subjects were provided with a general definition of physicality and visuospatial information:

- Material elements or characteristics such as shapes and shape elements
- Spatial arrangements and relationships perceptible through vision

Subjects were also provided with criteria which should not be considered as physical or visuospatial information, including:

- Orientation – subjects were able to rotate diagrams
- Overall Scale – diagrams were scaled to the approximate scale
- Contrast, line weight and quality – diagrams were uniformly printed

3.2.2 Understanding of Similarity

To ensure subjects shared the same general understanding of similarity, the following simple definition was provided:

- Corresponding physical elements producing some visual resemblance
- Shared physical characteristics of two or more diagrams

3.2.3 Diagram Illustrations

The experimental procedure represented Wright's plan diagrams uniformly on A5 cards. Each diagram was labelled from "*a*" to "o" and to ensure diagrams were presented in a consistent manner and to reduce any bias created by orientation, all A5 cards were labelled on the reverse-reflected corners. Plan diagrams were scaled to approximately the same scale, and were printed with the same line quality and contrast.

The objective of these criteria and definitions are to ensure that the responses obtained from subjects provide data from which to accurately compare and analyse any interrelationships which might exist.

3.3 RANKING TASKS

To study similarity assessments of design diagrams, three types of experiments were undertaken, which all required subjects to rank the 15 diagrams, , namely: a simple complexity-based ranking task, a target-based ranking task and a contextually dependent ranking task. Following each training period, each task was read aloud to subjects by the instructor (the author) as well as being displayed to subjects on a projector and their own individual computer screen as shown in Figure 2(a). The tasks performed by subjects in each experiment consisted of two separate phases.

(a) (b) (c) (d)

Figure 2. Experiment set up and testing environment showing: (a) Projected instructions, (b) and (c) sorting area and layoff space, and (d) individual results input monitor.

In phase 1 participants were given eight minutes in which to study and assess the similarities of the corpus. The 15 randomly ordered diagrams were given to subjects in a closed envelope. Participants were able to arrange the corpus on the layout space provided, Figure 2(b) and (c). Once the set time had lapsed, subjects were instructed to stop their assessment and commence phase 2 of the experiment.

In phase 2, designers were given eight minutes, in which to complete a spreadsheet and specify their responses. Once subjects' completed phase 2 they were then asked to describe those attributes used to rank diagrams. Based on the responses obtained from all three experiments, subjects' descriptions were divided into five general categories:

- individual shape type,
- feature types contained within individual shape type,
- arrangement or relationships of individual shape type,
- overall or bounding shape type,
- combination of the above, and
- unknown.

The following sections present the experiments and questions in further detail.

3.3.1 Experiment 1

The first question asks subjects to rank design diagrams from highest to lowest according to their complexity, where diagrams can be ranked equally.

Question 1 does not rely on any explicit contextual information and is defined as a 'default' ranking case since there is no design context and the assessment criteria is simply the physicality of the 2D diagrams themselves.

3.3.2 Experiment 2

Question 2 asks subjects to rank design diagrams from highest to lowest according to their similarity to a target diagram where diagrams can be ranked equally. The target diagram is also from Wright's design corpus: the Pope House; and belongs to the usonian period as shown in Figure 3.

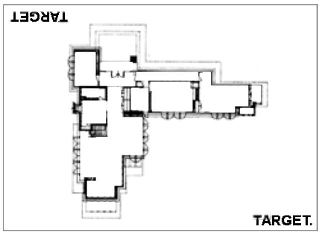

Figure 3. Target: the Pope House, 1940 Frank Lloyd Wright

3.3.3 Experiment 3

The final question specifies an explicit design context by defining a design task. This question utilises the 15 diagrams as a precedent library, which is to be considered by subjects prior to undertaking a design task. Using the brief provided, subjects must interpret the design requirements and assess the similarity of the 'precedent' diagrams in relation to the existing design, shown in Figure 4, and their interpretation of the design brief (see boxed text).

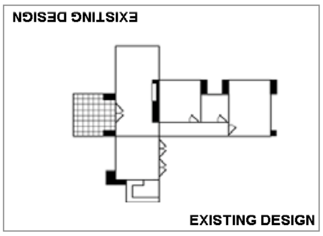

Figure 4. Existing sketch design used in design task.

Using the existing design diagram and the design brief subjects were asked to rank diagrams from highest to lowest according to their similarity to the design task.

Design Brief: Alterations and additions of an existing residential design are required to increase sleeping and living spaces, according to the following specifications of building layout:

- additional sleeping areas to accommodate two children;
- larger lounge, dining and kitchen areas; and
- outdoor living area;

Before undertaking this task a corpus of architectural plan designs is provided as precedents to assist you in designing.

4. Subjects' Responses and Analysis

No significant differences were found in subject responses based on the participant's level of design education, i.e., 1st (novice) or final year (expert) students. There was also no significant evidence found for differences based on gender or language. The following analysis of results considers the total of responses for each experiment. Tied ranks were normalized by the mean of the ranks for which they tie, assuming the number of ranks is equal to the number of diagrams compared.

4.1 TESTING HYPOTHESES

The first three hypotheses tested compare the responses among the subjects themselves and the last two hypotheses compare subjects' answers in relation to the results of the Q-SOM model.

4.1.1 Hypothesis 1: Subjects' similarity assessments will show correlation.
The first hypothesis is tested with Kendall's coefficient of concordance W for multiple rankings (Daniel 1978). Here, this test uses the normalised

subjects' responses such that each design diagram in each question has 15 different ranks.

The test statistic W for each question in Experiments 1 to 3 is shown in Table 2. For Question 1(complexity-based) and Question 2 (target-based) the value of W is relatively high with 0.53 and 0.75 respectively. Based on these results, the hypothesis can be accepted for responses to Questions 1 and 2 with a Type I probability equal to 0.13. The relatively large number of subject responses makes the test statistically significant.

The value of W for Question 3 (contextually dependent) is very low (0.21), which means there is little agreement amongst subjects. It is inconclusive as to whether this hypothesis can be accepted under the constraints of Question 3.

TABLE 2 Kendall's coefficient for Experiment Questions 1, 2 and 3.

	EXPERIMENT 1 TO 3		
QUESTION	1	2	3
W	0.53	0.75	0.21
p	< 0.66	< 0.85	< 0.98

The standard deviation of normalised ranks for each question can also provide an indication of whether the subjects' responses are more associated with particular ranks. It was expected that observers would agree on diagrams deemed to have higher similarity as well as those diagrams with lower similarity, i.e., first and last rankings, but there would be higher levels of discrepancy in the responses of those diagrams ranked in-between. Figure 5 shows that the agreement across Questions 1 and 2 does clearly follow this pattern, i.e., for the first four ranks and the last two to three ranks and is illustrated by the arc indicating higher levels of agreement.

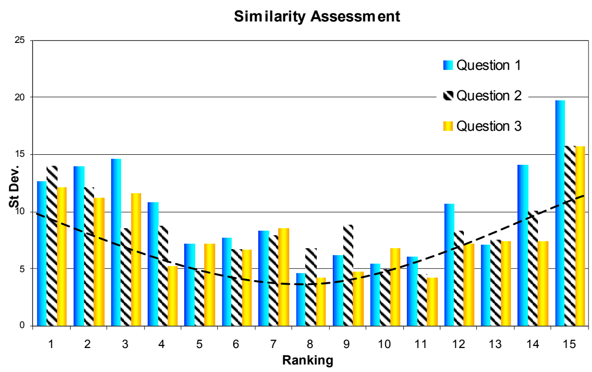

Figure 5. Standard deviations of rankings for Questions 1, 2 and 3.

Responses to Question 3 follow this pattern to a lesser extent and have a lower standard deviation corresponding to the lower coefficient of concordance *W*. This is evident in the graph from the lower level of standard deviation for ranks 11-14.

4.1.2 Hypothesis 2: Assessment of similarity is context dependent

This hypothesis assumes that if a subject's judgment of similarity depends on context; their answers should vary across different design contexts. To test the hypothesis subjects' responses to all three questions are compared and since the same subjects answered the three questions, it is assumed that his or her responses need not be in 100% agreement in order to accept this hypothesis. The normalised responses were averaged and this average was compared for each ranked diagram across different contexts using Kendall's coefficient of concordance *W*. The value of *W* for Questions 1-3 is 0.18, which is low and suggests that rankings are not associated with a probability greater than 0.92.

To make sure that the similarity among contexts could not affect the result of the test statistic, subjects' responses for only Questions 2 and 3 are compared since context is defined more explicitly in these questions, i.e., in the context of a target diagram in Question 2 and in the context of a design task in Question 3. To compare rankings, the Spearman rank correlation coefficient (Gibbons 1976) was used as the test statistic. This test statistic is also a measure of association. As such, r_s should be equal to +1 when there is a perfect direct relationship between rankings. The value of r_s for Questions 2 and 3 is 0.14. Like the value of *W*, the value of r_s is low, which suggests that ranks are not associated. Such a low level of agreement suggests that subjects would not give the same evaluation under different contexts and confirms the hypothesis.

4.1.3 Hypothesis 3: The visuospatial information used to assess similarity will vary depending on context.

As the previous test demonstrated similarity assessments are dependent on context. This hypothesis assumes that if a subject's judgment of similarity depends on context, the visuospatial attributes used to assess similarity will also vary across different contexts. Subjects' responses to the types of visuospatial information were normalized and plotted in the graph shown in Figure 6.

The graph shows the normalised responses for each question and provides an indication of whether assessments are more associated with particular attributes. Looking at the graph there is no one single attribute category that can be seen to be consistently used by subjects across the three ranking tasks. Significantly combinations of attributes were most commonly described by subjects across all questions. This category had the highest average response with 30.5% of subjects listing multiple features. This was followed by subjects reporting that they could not describe any attribute/s, with 22.5% specifying ‘unknown’. On average individual shape features scored the lowest number of responses with an average of 0.5% of responses describing some individual feature.

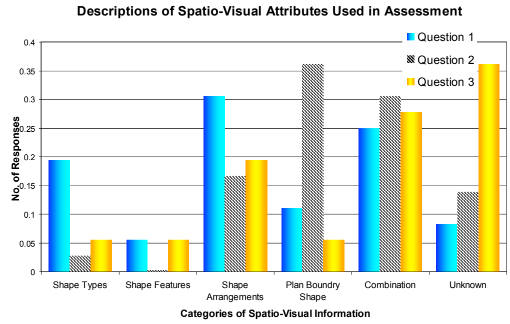

Figure 6. Responses of visuospatial attributes used in Questions 1, 2 and 3.

4.1.4 Hypothesis 4: An observer’s judgment of similarity should show some correlation with the results of the SOM networks.

This test compares subjects’ responses with the results of the Q-SOM model. The test assumes that the similarity and therefore types of features identified by the model may also be important in designer’s judgments. As the previous two tests demonstrated similarity assessments are dependent on context and the features used by subjects will also vary accordingly.

Comparisons are based on four networks, where two of the best performing networks and two of the worst performing networks were analysed. These networks were chosen based on the results from Precision Matrix, JAC and FM analysis methods. The hypothesis is tested with the Spearman rank correlation coefficient. Analysis is based on the normalized subject responses and compared to the ‘ranking’ derived from networks using the activation values of each SOM’s output nodes. The test statistic r_s for Questions 1 to 3 are shown in Table 3.

TABLE 3: Spearman rank correlation coefficients between subjects’ responses and the Q-SOM model with the two best performing networks.

PERFORMANCE	NETWORK	SPEARMANS RANK	Q 1	Q 2	Q 3
BEST	5X5 CFS with TF*IDF	$r_{s\,n}$	0.62	0.70	0.38
	5X5 FB with TF*IDF	$r_{s\,n}$	0.59	0.73	0.32
WORST	3X3 CFS with FREQ.	$r_{s\,n}$	0.13	0.18	0.13
	3X3 FB with FREQ.	$r_{s\,n}$	0.15	0.12	0.09

Table 3 shows all values of r_s vary significantly across all questions and networks. Values of r_s for Questions 1 and 2 and the two best performing networks are all above 0.59, with the highest value of r_s for Question 2 with 0.73. These high values support the hypothesis that the subjects' responses and the Q-SOM model are associated with a probability of 0.78. However, the network which returned on average the highest values of correlation with subject responses was not the best performing network as determined by internal performance measures. Instead, the second best performing network, i.e., the 5x5 CFS network with TD*IDF weights has on average the highest values across all questions, with the except of Question 2. As expected the values of r_s for Questions 1, 2 and 3 across all of the worst performing networks are significantly lower than those values of the best performing networks.

This hypothesis must however be rejected for Question 3 which uses contextually dependent similarity assessment. Here, values for the two best and worst performing networks are significantly lower with 0.38 in the best case and 0.09 in the worst.

4.1.5 Hypothesis 5: Correlations between an observer's judgment and computational assessment improves when context is not considered

Based on the confirmation of Hypothesis 4 for Question 1 and 2, this test uses the same approach to evaluation, i.e., the Spearman rank correlation coefficient, but considers only Question 1 which has no explicit contextual information. Recalling that Question 1 asks subjects to rank the similarity of diagrams based on their complexity, this test compares the subjects' responses and the results of the two best performing networks. The values of r_s are relatively high, which means that there is an association between the subjects' answers and the 5x5 CFS network with TD*IDF weights and 5x5 FB network with TD*IDF weights as shown in Table 3.

These results support the hypotheses that when context is not considered the two best performing networks are able to match designers' judgments. It is inconclusive as to whether networks can better match them when certain types of contexts are not considered. If we consider the value of r_s for Question 2, where context is implicitly defined in the target diagram, the correspondence is higher resulting in a greater association between subjects' responses and the results of the two best performing networks. If we consider the correlation between responses to Question 3 (a contextually dependent task) and the networks, it is significantly lower. The testing of this hypothesis is therefore inconclusive.

5. Discussion

The objective of these cognitive experiments was to evaluate correlations between the subjects themselves and between subjects and the results of the Q-SOM model. An important observation from the results reported here is that although subjects' responses are associated, in comparison to previous experiments of feature-based similarity (e.g., 0.90 in Tversky's 1977 experiment) the degree of concordance (Section 4.1.1) among subjects' answers is only satisfactory, ranging from 0.21 in the worst case (Question 3) to 0.75 in the best case (Question 2). This lower degree of concordance may be due to the complexity and number of design diagrams that were evaluated and the use of a target diagram (Question 2) and design task (Question 3).

In other research on semantic similarity assessment human-subject experiments have been used to determine the effectiveness of computational models. These experiments found a correlation of 0.79 using an information content approach (Resnik 1999), and 0.83 using a distance approach (Jiang and Conrath 1997). The results reported here are not directly comparable, since here similarity is visuospatial, whilst these other studies evaluate similarity among the semantic relations of textual terms. Our results appear to support the use of the Q-SOM model for feature-based similarity of 2D diagrams, where correlation between the model and the subjects' answers was 0.32 in the worst case (contextually dependent) and 0.73 in the best case. Analysis shows the performance decreases when a design task is explicitly defined.

In cognitive studies of similarity assessment outside the design domain, it has been shown that goal-oriented similarity assessments vary with the task at hand (Landry et al. 2001). It might be concluded that since design scenarios are by nature 'open', ambiguous and interpretive that they result in other criteria, perhaps non-visual such as a designer's preferences and existing design experience, playing a larger role in assessment.

Other studies have shown that with practice, individuals develop representations of features that are useful for the task at hand and are treated as single units through processes of differentiation and unitization (Goldstone 2003). If a feature varies independently of others, or occurs more frequently, observers may develop a specialised detector for that feature (Goldstone, 2003). When specific information about a feature is known, it has been shown to take precedence (Heit and Rubinstein, 1994). In other studies of unsupervised category learning of visual patterns, experiments show that individuals are also sensitive to the frequency with which features of visual stimuli co-occur (Edelman et al 2001).

The results presented here have shown that during assessment, and especially in the context of a design task, visual sorting largely depends on combinations of visuospatial information and designers may not be able to describe the features used during assessment. Subjects were not able to describe the basis for their decision procedures. On average 22% of subjects could not specify the visual attributes used to assess similarity. This outcome could be expected in the design domain since the similarities which can be distinguished in and between design diagrams can be based on a variety of attributes belonging to relatively complex geometries. Goldstone and Son (2005) have also illustrated that individuals are still able to make similarity assessments even when the exact properties of relevance are unknown.

Cognitive studies undertaken in design on the types of information categories utilised during drawing (Suwa and Tversky 1996, 1997) have shown that designers process information at multiple levels and shift focus between varieties of information categories based on their current strategy. Using a retrospective protocol analysis Suwa and Tversky (1997) found that architects are able to perceive visual attributes in diagrams such as shapes and angles and are able to "read-off" more abstract features and responses, pursuing design thoughts more deeply. They concluded that the design process consists of cycles of focus shift, supporting the view of a two-way bottom up and top down approach to perception. This supports the multi-level approach to information processing adopted by the Q-SOM model where both local and global visuospatial information is utilised.

The results obtained from attribute descriptions made by subjects also suggest that the local-versus-global argument is ill-posed and that either one may dominate depending on the intention of the designer. According to Kinchla et al (1983), the observer has the ability to select alternative visual strategies, sometimes attending to the local details and sometimes attending to the global properties. The multiple levels of abstraction that are supported by the Q-SOM model enable both low-level geometric and high-level semantic feature to be utilised by the network for similarity assessment.

Finally, although our results found no significant differences in how 1st year versus final year design students assessed the similarity of Wright's diagrams, it was informally noted that the majority of 1st year design students finished prior to the time allotted whilst almost all final year designer students required the full time allocated to complete each experiment. Other researchers have also shown that knowledge and design experience can influence the comprehension of graphic information (Gobert 1999) as well as the type and frequency of those visual features detected (Akin 1978, 1986).

6. Conclusion

This paper has investigated how human-subjects (designers) assess the similarity of 2D design diagrams using a variety of assessment techniques. The overall objective of this research is to increase the Q-SOM model's performance through further cognitive evaluations and computational experimentation so as to find those network and feature variables, which on average, perform as well as possible in relation cognitive assessments.

Following recommendations made by Cook and Campbell (1979) on the types of validity which may be attained for models of causality, it is proposed that analogous dimensions of validation be followed here. If it can be shown that the Q-SOM model embodies all of the following four dimensions of validation then the approach is more likely to be of utility and significance. Two of the four dimensions have already been tested here and based on our results can be explored further, namely:

(i) *statistical conclusion validity*, i.e., are there similarities between the diagrams?

(ii) *external validity*, i.e., given that there are similarities, how generalisable are these results across different network types, persons and contexts?

In addition, two other important dimensions must now be tested, including:

(iii) *internal validity* i.e., given that there are similarities, is it causal from particular operational variables?

(iv) *construct validity* i.e., given that similarity is causal, what are the particular cause and effect constructs involved?

Utilising these dimensions of validation will ensure that the Q-SOM model will be capable of measuring similarities of 2D design diagrams in a cognitively congruent manner. This will also allow explicit examination of how particular network, featural and contextual variables affect similarity assessments. Patterns of information flow within the network can then be examined, allowing for hypotheses concerning the type and weights of features used to distinguish 2D diagrams to be investigated in relation to those features described by designers as being salient in assessments.

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SESSION SEVEN

Espoused theory and theory-in-use: Denys Lasdun's design credo
G. Goldschmidt

Accidental resource
A. Heylighen, W.M. Martin & H. Cavallin

The semiotics of product aesthetics
N. Crilly & P.J. Clarkson

Implications of metacognition in design
J. Jänsch & H. Birkhofer

Critical points for change
P. Parthenios

Modelling technology enhanced learning environments through designers observations
M. de Grassi, A. Giretti & M. Mengoni

Exploring the effects of introducing real-time simulation on collaborative urban design in augmented reality
S. Attfield, C. Mottram, A.F.G. Schiek, A. Blandford & A. Penn

Architecture design intelligences
N. D'Souza

JS Gero and N Bonnardel (eds), *Studying Designers'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 335-341

ESPOUSED THEORY AND THEORY-IN-USE: DENYS LASDUN'S DESIGN CREDO

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Abstract. This paper looks at the design principles of Denys Lasdun, a major modern movement British architect. Writings by and about Lasdun are used to derive some salient design beliefs, concepts and principles held by Lasdun that explicitly informed and guided his design activity, thus forming his "espoused theory". Lasdun's design principles and values are also inferred from a think-aloud protocol of a design experiment undertaken by him in 1992, from which we construe his "theory-in-use." The conclusions from both analyses yield a rich picture of this architect's design theories, both implicit and explicit.

1. Introduction

We are all aware of the fact that people have theories about most things in life. However, people do not always look up their explicit views on most issues before taking action. In fact, we are required to make decisions, act and react all the time, often right away, which makes a conscious consultation with our learned theories rather impractical, if not impossible altogether. What then guides our decisions, our actions? Argiris and Schön (1974) coined the terms "espoused theory", which designates a theory one believes in and subscribes to, and "theory-in-use" which is, in contrast, the theory according to which one actually acts in practice[1]. They point out that oftentimes these theories are not identical, although we are usually not aware of differences unless we train ourselves to attend to them. Argiris and Schön were interested in this dichotomy in the context of professional practice and learning. We adopt the terminology and use it in the context of the design philosophy and design conduct of a professional architect, whose espoused theory and theory-in-use we shall describe and compare.

2. Espoused theory

The architect in question is Denys Lasdun (1914-2001), an influential British architect who designed, among others, the National Theater (Figure 1), the Royal College of Physicians in Regent's Park, the Bethnal Green and St James's Place apartment buildings – all in London; The University of East Anglia (master plan and major buildings) and buildings for other universities in Britain, as well as the European Investment Bank in Luxembourg (Figure 2). Lasdun was an ardent Modernist, much influenced by Le Corbusier.

Figure 1. Sketch for the *Figure 2.* The European Investment
Bank,
National Theate Luxembourg

Over the years he developed a solid professional world-view which he endeavored to translate into design principles to be implemented in the specific projects he worked on. He remained faithful to his views even when they fell out of vogue in the 1970s and 1980s (later he enjoyed a comeback; the Royal Academy featured a retrospective exhibition of his work in 1997). Taken together Lasdun's oeuvre, and the principles that informed its creation, can be described using Gruber's term "network of enterprises" (Gruber 1989), by which he means a series of interrelated works by a creative individual who works to achieve specified ends. In a similar vain, and specifically in architecture, Anderson (1984) found that architects undertake systematic "research programs" which they develop from one project to the next.

Lasdun admired and befriended theoreticians (e.g., John Davies, William Curtis) and was inspired by them, but shied away from defining his own theoretical constructs as "theory" or "philosophy." He saw himself as a practitioner whose role it is to design buildings and not voice theories:

> "Buildings should speak for themselves but they are motivated by ideas. In turn, buildings impose their own laws to which the ideas must submit. Ideas do not constitute a systematic philosophy but rather certain deeply felt maxims. These provide a foundation on which the various activities of a modern practice may rest." (Lasdun 1976, 7).

Lasdun did subscribe to maxims that converge to form a vision, an espoused theory (of action). He believed the organization of a building is most important; the structure – in an over-arching sense – "can illuminate the basic architectural task." He maintained that a design solution must be harmonious in that at every scale the combination of disparate elements must produce a unity, and in order to achieve harmony and unity research and experimentatin must be undertaken, among others via the making of models (Figure 3).

Figure 3. Models made for the National Theater

Lasdun was very context-minded and thought the givens of a site, especially existing buildings in an urban setting, must be respected and responded to:

> "… no building is an isolated, separate thing in the sense that a poem or a painting can be. All building and indeed all planning is part of a larger plan… The links and the spaces between the buildings and the relation of one to the other, of new buildings to old in space and time, are just as important and just as worthy of architectural study as the buildings themselves…" (Ibid., 108).

Curtis (1994) generalizes and says that Lasdun "spoke of an 'object-found philosophy', meaning a sensitivity to the givens of programme, site and culture. He [Lasdun] also stressed the importance of reading the context when searching for forms." (p. 55).

Lasdun was also very concerned with people's needs, their ease of functioning, and their social interactions:

> "…You cannot have form, in architecture, which is unrelated to human needs; and you cannot serve human needs in terms of architecture, without a sense of form and space. Architecture, for me at any rate, only makes sense as the promoter and extender of human relations."[2]

Lasdun's mature work commands much respect in Britain and elsewhere, for reasons that Dannatt (2001) summarized so well in his obituary: "…his singleness of purpose, the outstanding ability to extract formal architectural order out of so many diverse building tasks and heighten it to a level of eloquent dominance." (p. 27). The following is a summary of relevant design principles we find in Lasdun's espoused theory:

- Formal architectural order
- Harmony and unity at every level
- "Object-found philosophy": maximizing the opportunities of each project
- Importance of organization, program, site, and other contextual information
- Sensitivity to social needs at the level of the community and the individual
- Importance of research and experimentation through scale models

3. Theory-in-use

In the think-aloud design exercise that Lasdun agreed to undertake he was asked to react to a "footprint" of a suburban branch library which had six entry options[4]. The footprint was an irregular shape enclosing some 340 sq.m. in a single storey (Figure 4). Lasdun was irritated by the given shape and called it throughout the exercise "unattractive", "rigid", "like a jigsaw puzzle", "purely numerical, purely area" and said: "I don't think there's a future in this configuration", "you would get rid of all this stuff, because I can't see what it is doing, it has no meaning" and "It hasn't responded either to organization, or site or context. So there's nothing there." (Figure 5). He concluded: "I would destroy that design, that configuration, and wouldn't accept it."

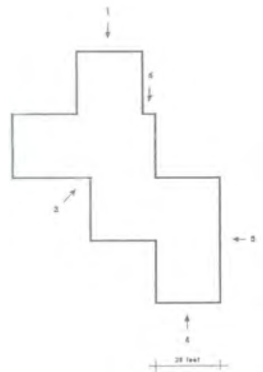

Figure 4. The library exercise

*Figure5.*Lasdun's first library sketch (note encircled annotation on the right: O[rganization], Site, context)

The statement concerning organization echoes his statements about the importance he attached to site, context and organization, as witnessed by some of the quotes above. He complained that there is no information regarding the organization of the library, how it functions, and added: "I would tell immediately that that form cannot respond to a good organization…" and later: "I don't know what sort of library it is. Is it a central reception; is it stack; how do you get your book, how do you go out with your book." He talked about the social function of libraries and said it depended on location, among others: "how it stands in relation to where people live and work." In this case "there are no clues on this." He said research was necessary; he would have to study a host of issues before he could tell what the design would be. Dannatt (2001) remarks that "Lasdun saw every building as a piece of true research intensively conducted at every stage." He quotes Lane[5] who listed five distinct design stages that were typically followed in Lasdun's practice: 1) Research: the study of all facts relevant to the project; 2) Finding the "soul of the building", i.e. a "generating idea"; 3) Building of a scale model; 4) Clarification of the concept and development of the design in detail; and 5) Building of a presentation model and production of construction documents.

In the library exercise Lasdun approached the assignment in precisely the same way. By definition he could not go beyond the first stage, but it was frustrating to him that he could not complete that stage properly because of missing information and because of the given configuration which he could not accept. He was reluctant to make assumptions regarding site, context or organization but was willing to try to come up with ideas given the freedom to transform the configuration. He was careful not to change the area, out of respect to (estimated) clients' prerogatives – again a trend we have encountered in his writings. He tried three configurations: a rectangle of the same area, and two compositions of the two L shapes that the configuration can be divided into (Figure 6). It must be noted, though, that he did so under protest and continued to complain about the inadequacy of the givens. The emerging picture gives us more than a glimpse into Lasdun's theory-in-use.

Towards the end of the exercise he was willing to accept a scenario according to which an existing building (the footprint) and the lot on which it is built are donated to a small community that decides to convert it into a library. He then enclosed the lot by a wall and turned the land around the footprint into a garden with a meandering path leading to the entrance (Figure 7). Under these circumstances, he said, the configuration was acceptable and it did not matter where the entrance was. He warmed up to the problem and said "I quite like this idea"; the architectural idea was minimal but he was satisfied with it: "you are presented here with a nice garden wall, with a nice gate in it; it says "Library", it says what it is… Rather nice, very simple wall statement… In which case that [given configuration] should remain. It's no longer being asked to be changed, either organizationally or from an architectonic point of view." So realistic did it become that he wondered who would pay for the garden wall…

Figure 6. Lasdun's second library sketch

Figure 7. Lasdun's final library sketch

The protocol tells us the story of an uncompromising architect who sticks to his principles but once conditions meet a minimum level of acceptance, he can live with the situation and immediately finds a way to see the problem in a different light, under which he can easily resolve the conflicts. This is a fine example of Lasdun's "object-found philosophy" (Curtis 1994). In fact, at this point he may have been unable to resist the opportunity – or shall we say temptation – to come up with a design solution, and he found ways to be flexible enough about a host of issues that could be molded until they fitted into his life-long design credo. It should come as no surprise that Denys Lasdun never stopped practicing architecture until the day he died, shortly after his 86th birthday.

The design concerns revealed in Lasdun's spontaneous verbalization represent his theory-in-use, which is very close to his espoused theory:

- Lack of formal order is irritating
- A simple design solution is adequate if it responds well to needs
- Information about organization, site and context is indispensable
- Social considerations are important (where people live and work)
- Clients' need must be respected
- Research must be conducted

We conclude that contrary to what Argiris and Schön's might have predicted, in Lasdun's case his design theory-in-use was highly congruent with his espoused design theory. The flexibility he demonstrated when he found an idea that he liked may represent a small deviation from the sacred credo he so ardently adhered to, which comes to show that ideas have the upper hand over design principles that are by no means immortal. In Lasdun's own words: "at any moment someone may build something so unexpected yet so compellingly right that it will make all talk about trends and philosophies vein." (Lasdun 1976, 107).

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Notes

1 Argiris and Schön were inspired by Kaplan (1964) who distinguished between espoused logic and logic-in-use: their espoused theory (of action) and theory-in-use constitute an analogous distinction.

2 Denys Lasdun, quote from Royal Gold Medallist Address, 1977.

3 *The Times*, January 12, 2001.

4 The "library footprint" exercise was devised by Donald Schön and William Porter in 1986 for a design thinking research program at MIT. The exercise was deliberately vague in order to study designers' interpretations of the task.

5 Graham Lane was an associate in the Lasdun partnership.

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ACCIDENTAL RESOURCE

A Fable of Design Research through Storytelling

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Abstract. Building Stories, an experimental course at the University of California-Berkeley, started its first semester with a carte blanche opportunity and generous support from leading architecture firms in the San Francisco Bay Area, to try and unlock the knowledge capital embodied by architectural practice through storytelling. Five years later, the methodology and resulting stories turn out almost coincidentally to provide a unique resource to study design and designers "in the wild". After introducing the underlying ideas of Building Stories and their implementation as an operational methodology, the paper reports on its use in three research projects that study quite different aspects of design: the notion of collaboration in the architectural profession, the role of ethics in design practice, and the specific nature of architectural knowledge.

1. Introduction

The past four decades have witnessed a slow but steady growth in empirical studies of design, starting with Eastman's pioneering work in the domain of architecture (1969). Of all empirical research methods that meanwhile have been adopted to investigate design activity (Cross 2001), think aloud protocol analysis has received the most use and attention in recent years, especially since the 1994 Delft Design Protocols Workshop (Cross et al. 1996a).

Although arguments for accepting think aloud protocols as reflections of cognitive activity are well documented and substantiated (Ericsson & Simon

1984), the technique shows serious disadvantages when applied to design. Since visual, non-verbal thinking is fundamental to how designers know and work (Cross 1982), verbalization may produce side-effects that change the subjects' behavior and cognitive performance (Cross et al. 1996b). Research in product design revealed that protocol analysis, and the theoretical and methodological constraints it brings, interferes with designing (Lloyd et al. 1996). Moreover, valuable as it may be to capture a few aspects of design thinking in detail, the technique fails to encompass some of the broader realities of design in context (Cross 2001). Ignoring the contextual dependency and social articulation of design competence offers too limited a perspective for understanding design as it is practiced (Bucciarelli 2001).

These broader realities of design are the focus of Building Stories, the topic of this paper. Strictly speaking, Building Stories is not (and was not intended to be) an empirical research method for studying design, yet its outcome seems to provide a valuable resource for design researchers. The following sections introduce the underlying ideas of Building Stories and their implementation as an operational methodology, followed by its use in three different research projects.

2. Building Stories in a Nutshell

Since architecture tends to deal with unique projects, much of the knowledge involved is experience-based, tacit and embedded within the act of designing (Schön 1983). Despite this intimate relationship between knowing and designing, architectural practice is not—and has never been—documented and studied systematically. Apart from a few isolated pilot efforts, there are no consistent actions to establish and maintain access to the profession's knowledge, let alone to extend its potential reach.

This observation triggered the development of Building Stories, a program to engage teams of students, interns, young and seasoned professionals in capturing and exploring the tacit knowledge embedded in real-world building projects (Martin et al. 2003). Inspired by the power of storytelling in knowledge management (Denning 2001), the teams develop stories—narratives intended to convey what is going on and what is significant to those involved—about buildings that are in the process of being designed or built. Stories are not only direct, easy to read and entertaining; they respect the intricate relatedness of things, in a way that makes them easy to remember afterwards (ibid.). As such, the story format provides a dense, compact way to deal with and communicate the complexity of real-world design in a short period of time.

So far, Building Stories has been applied in two flavors: the original, all-in version takes shape in an experimental course spanning an entire semester; the light version is a one-week workshop, which essentially squeezes the activities of the original version into five intensive days.

'Building Stories: A Case Study Analysis of Practice' is an experimental course offered in the Architecture program at the University of California-Berkeley. Students enrolling in the course (some part-time interns in the early phases of their professional careers) develop a theoretical and methodological framework for undertaking a case study through storytelling, grounded in the empirical facts of the project. Weekly lectures/discussions make students familiar with the methodology and with critical questions needed to explore the richness of the stories embedded in a building project. Meanwhile, they actively engage in developing stories about a specific project that is being designed or built. The architectural firm designing the project selects an advisor who provides access to all relevant information. This advisor regularly teams up with students and interns to discuss the project and evaluate progress of their stories. The firm, at its discretion, may also introduce team members to consultants and other professionals involved in the project's design, management and construction.

At the end of the semester, stories are posted on a public website, making the experience and insights captured worldwide accessible. As such, Building Stories could serve as a means for sharing knowledge and experiences from practice with students, educators, researchers and colleagues (Martin et al. 2005). However, the growing on-line story repository is but one mechanism of knowledge exchange in Building Stories. An additional mechanism derives from the inherent heterogeneity of the teams in terms of the skills and experience team members have (Heylighen et al. 2005). As the semester ends, the temporary network of students, interns and professionals dissolves. Yet what they have learned from each other creates a competence that becomes highly valued in their respective environments—practice or academia. The expertise and hands-on experience of the professionals in the team enable students and interns to develop a critical understanding of the issues and tasks of design practice. In return, the students' participation assures a continued supply of competencies trained in the latest research skills and techniques. Moreover, the (academic) knowledge networks they have access to, and the time and energy they can invest, make them highly attractive to practice. This newly acquired competence—the skills, attitudes and perspectives that follow participants to other projects and contexts—seems at least as important and valued as the on-line story repository.

3. DESIGN IN THE WILD

In fall 2005, a seminar entitled 'Building Stories Revisited' was organized to look back on the previous five years and evaluate the initiative from various stakeholder perspectives. Three researchers, who enrolled in the seminar as part of their Ph.D. program, were asked to confront their research topic with Building Stories, both as process (approach, methodology) and as product (the stories available on-line and the corresponding projects). At first, the researchers were highly skeptical about the capacity of Building Stories as vehicle for knowledge transfer. Yet eventually, the story collection as well as the methodology ended up being a surprisingly valuable resource for their Ph.D. research, providing a unique opportunity to explore their topics and hypotheses “in the wild”.

3.1. COLLABORATION

One researcher investigates the variable signification of collaboration in the architectural profession (Doctors 2004). Collaboration is a cultural practice of two or more individuals working together on a task or project, and intrinsically provides a framework for producing, sharing and contesting knowledge. Many disciplines commonly employ collaboration and have studied its efficacy from social, economic, and cultural perspectives. In architecture, however, the use of the term is often misleadingly interchanged with that of coordination, cooperation or communication. Moreover, it rarely evidences consideration for the wide variability spanning from the utopian Ruskinian interpretation of medieval-era trade guilds to its polemical challenge of the architect-hero paradigm.

Analysis of Building Stories revealed both the process and the product to be peppered with instances of collaboration (whether or not termed correctly). Key to the methodology is the participation of students, interns and professionals working collaboratively toward shared authorship of tacit knowledge derived from a story. In this collaborative process, the roles and rules for engagement are most likely more implicit than explicit, and the responsibilities are largely distributed according to each participant’s skill set, interests and availability. Yet, while working in this horizontal decision-making model, participants are learning about the various (other) shapes collaboration can take. The stories about the new De Young Museum project, for instance, provide unique insights into the tactical challenges of establishing a workable organizational structure and methodology to compensate for geographical and cultural differences among non-collocated team members.

3.2. ETHICS

Another researcher studies design ethics in practice. While revisiting Building Stories, she identified various points in the stories where decisions have been made and other points where they *could* be made, if there were to be a level of explicitness and consciousness about opportunities for ethical consideration in the design process (Becker 2004). A case in point is the Pottery Barn. From the start of the project, politically active community groups expressed concern about a national chain store and its impact on the future of the neighborhood, which drew a lot of media attention and triggered attempts to influence the approval process. In the Berkeley High School story, conflict arose between those wanting to generate income for their business and those having a deeper sense of historic preservation and life outside the margins of a project's financial gain. The researcher came to realize that moments like these—where multiple interests conflate and conflict, or even where one begins to *sense* conflict, moments in which the progress of a project is threatened—are precisely the potentially deliberative moments, those in which ethics would logically be addressed. Clarifying the multiple points of conflict that became (or could have become) sites of reflection within the Building Stories might become a first step towards establishing a new model for ethics in practice.

3.3. KNOWLEDGE

The third researcher explores the nature of professional knowledge in architecture (Hoque 2004). Extensive literature study inspired the hypothesis that architectural knowledge is a performative (Austin 1975): it does not consist of a particular set of ideas, themes and theories, but rather of how these ideas, themes and theories are worked through to produce architectural artifacts. Confronting this hypothesis with the Building Story collection revealed the notion of performativity to be very apt in describing what occupies the architects involved in various projects, such as the Golden Gate Parking Structure, Berkeley High School and the UCSF Medical Educational Research Center.

4. Conclusion

Advancing storytelling as a vehicle for studying design might look like dragging the Trojan horse into the walls of research. For inside these walls, storytelling is often viewed as, if not suspect, than at least disputable, and in any case of no more than secondary importance, at best useful for illustrative purposes. This antagonism toward storytelling can be traced back as far as the time of Plato, who identified poets and storytellers as dangerous fellows putting unreliable knowledge into the heads of children, and reached a peak in the 20^{th} century with the determined effort to reduce all knowledge to analytic propositions, and ultimately physics or mathematics (Denning 2001).

This analytic approach, however, does not fully fit the uncertainty, the value-conflicts, the unexpected changes, the confusion, the chaos, in short the living core of what is involved in real-world design. Part of the business of designing is undoubtedly captured by think aloud protocols or controlled experiments, yet to reduce the living complexity of architectural practice to that part is just that—a reduction. In view of this, initiatives like Building Stories may have relevant and important complementary contributions to make to the understanding of design and the nature of design activity. As Bucciarelli (2001) contends, a good story is a truthful story and, like a scientific theory, can be put to the test, making sense to the participants as well as to 'outsiders'. It relies upon the facts observed as well as metaphor, and as such is open to different interpretations. This does not necessarily mean, however, that it is "unscientific": "*the claim here is that a good story which has depth [...] in allowing for varied interpretations, avoids the over-simplification of a behaviorists model or cognitive scientist's mapping and as such is in closer touch with reality—however that is construed*" (Bucciarelli 2001:300).

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THE SEMIOTICS OF PRODUCT AESTHETICS

Investigating the role of designer intent in determining product form

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Abstract. This short paper reports on ongoing research that seeks to develop a comprehensive perspective on product aesthetics. This includes an interview-based qualitative study into the role of designer intent in determining product form. A brief discussion is provided here on preliminary results relating to the nature of design authorship and its influence on intent.

1. Introduction and motivation

A semiotic perspective on industrial design views the product as a text that is 'written' by designers and 'read' by consumers (Monö, 1997). In the realm of product aesthetics, considerable effort has been focused on studying how products are interpreted and what factors influence that interpretation (Crozier, 1994; Bloch, 1995; Crilly *et al.*, 2004; Creusen and Schoormans, 2005). In contrast, the designers' role in shaping those products, and other factors that contribute to its eventual appearance, have been relatively ignored. Therefore, whilst the 'reading' of products has been examined in some detail, the 'writing' of products has been granted far less consideration. In particular, little attention has been devoted to the designers' intentions for how the product's form should be interpreted by consumers.

The majority of design literature related to product aesthetics assumes that designers consciously intend to evoke specific kinds of consumer response and that this intention is influential in determining product form. It is often implied, therefore, that the more understanding that is gained of consumer response, the more informed designers can be in generating product form. A lack of information on how product form determines consumer response is thus assumed to be a limiting factor in designing visually successful products. These assumptions are presumably based on the researchers' personal experience, anecdotal evidence or preconceived notions of design practice. However, such foundations are not often stated and are not available for examination by other researchers.

Whilst exploring the relationship between product form and consumer response is of interest, it has not been established how such knowledge would be used. Furthermore, even if designers *do intend* to evoke consumer response, a number of factors remain unexamined. Firstly, from where do these intentions originate, how might they be categorised and how are these abstract intentions translated into tangible product form? Secondly, beyond designer intent, what other factors are influential in determining product form? For example to what extent are intentions preserved through the processes of negotiation, manufacture, distribution and retail? Thirdly, what effect does feedback on the eventual consumers' response have on subsequent design activities?

These unanswered questions suggest the need for a study examining the relationships that designers have with the aesthetics of their products and, more specifically, the role of intent in design practice. Such a study would thus test the implicit assumptions of existing work and suggest new directions for future work. In addition to the absence of published literature on the subject, recent developments in the design field also demand a new study. For example, the continued rise of 'the brand' as a central design issue and the advent of formal consumer research as an input to the design process have changed the nature of industrial design practice. Thus, literature published before these factors attained such prominence may be somewhat dated in their treatment of the requirements, constraints and sources of inspiration that influence design practice.

2. Method

By adopting a grounded theory approach (see Glaser and Strauss, 1967), a qualitative research study was undertaken to examine the issue of designer intent in industrial design. The study focused on consultant design practice, sampling from the London and Cambridge areas of the UK. The sample was complemented by including professional consumer researchers whose findings feed into the design process. Over the course of one calendar year (2004), 28 interviews were conducted with a total of 29 interviewees representing 23 different organisations. All the interviews conformed to a semi-structured protocol, eliciting the interviewees' attitudes on the topic whilst remaining open to unanticipated but relevant themes (see Fielding and Thomas, 2001: 124).

The study included an initial series of eight exploratory interviews with industrial designers discussing the topic in relation to their general professional experience. This was followed by a further series of 13 case-based interviews with designers, each focusing on one particular product.

The seven interviews with consumer researchers were conducted in an exploratory manner, similar to the initial interviews with designers. The majority of the interviews were conducted on a one-to-one basis and set in the context of the interviewees' places of work; the mean duration of each interview was one hour and 40 minutes. At the end of each interview, the interviewees were presented with diagrammatic representations of the researcher's current conceptualisations of the domain. This allowed the researcher to gain the interviewees' appraisal of the work and also elicited further contributions on the research topic (Crilly *et al.*, 2006).

With the interviewees' permission, all the interviews were recorded and later transcribed to produce over 250,000 words of text-based data. This data was subjected to grounded theory coding practice, as described by Strauss and Corbin (1998). That is, themes of relevance were identified and sections of the transcripts were labelled (coded) with these themes for easy identification. As new themes and sub-themes were identified in the data, the transcripts were continually coded and re-coded as necessary. Reviewing all the transcript segments that had been assigned the same codes facilitated the identification of connections and contrasts within the data. Computer-aided qualitative data analysis software, QSR NVivo (2002) was used to assist in this task and to provide interactive visualisations of the emerging themes. Based on this analytic procedure, an interpretation of current industrial design practice was obtained which places the role of designer intent within the context of other factors that are influential in determining product form.

3. Selected preliminary results

There is insufficient room here to draw together the various themes that were explored in this study. Instead, a quick introduction to designer intent is provided, followed by consideration of how the nature of that intent is influenced by the degree of 'authorship' attributed to the designers.

3.1. DESIGNER INTENT

Most designers do not explicitly define themselves as communicators, but are aware that their designs have communicative potential. Therefore, with varying degrees of self-reflection, they generate their designs under the assumption that their 'message' will be interpreted by others. However, obliquely this idea of message formation is understood, designers often strive to affect consumers with a positive experience, one that makes the product desirable and encourages consumption. Thus, most designers form clear objectives for how their products should be perceived. They then translate these intentions into physical form whilst accommodating many conflicting constraints. Following the manufacture of the product, embodiments of the original intentions are then available for the consumer to perceive.

3.2. DESIGN AUTHORSHIP

Within the range of consultancy practices there is variation in the degree of ‘authorship’ attributed to the designers. At one extreme, there are the ‘artist-designers’ who posses their own style and who are, in effect, their own brands. At the other extreme, are the ‘contractor-designers’, who perform a piece of design work for the client and adapt their style to suit the brief. Products designed by the artist-designers often exhibit a distinctive set of visual characteristics and are easily identifiable as the work of that individual. Conversely, the personality of the contractor is almost invisible in the finished product as their own preferences are subsumed by the needs of the client. In between these two extremes are the spectrum of ‘consultant-designers’ who collaborate with the client in defining what is required but who still produce products somewhat anonymously. The majority of the interviewees in this study fell into the category of consultant-designers and this mode of operation reportedly typifies industrial design practice. However, artist-designers were also represented in the sample and it is worth noting here some of the distinctions that can be drawn between the nature of their intentions and those of their consultant counterparts.

Because of their relative fame, artist-designers are freed from many of the constraints that characterise consultant design practice. Importantly, they are often approached by their clients for their distinctive aesthetic, and therefore their own visual sensibilities or preferences are expected to strongly influence the product; in many cases that is precisely what the client is paying for. Furthermore, the clients’ brand, which is central to consultant design practice, may actually be subservient to the artist-designers’ *own* brand. That is, the artist-designers’ brand heritage, brand values and brand aesthetic may dominate or replace those of the client. This means that in the marketplace, the resulting product, or range of products, is presented as a separate brand to that of the client (or a sub-brand within it). With respect to designer intent, these privileges of the artist-designer distinguish them from their consultant counterparts by freeing them to design for their own aesthetic satisfaction rather than those of the eventual consumer. They therefore claim to be unconcerned with anticipating consumer response and do not consciously strive to evoke specific reactions.

This distinction between different types of designer is somewhat arbitrary as all designers may exhibit characteristics of each type at different times and on different projects. Furthermore, no designer is entirely free of technical, financial or political constraints, nor are they able to design in a fully objective manner. However, the consultant-artist distinction is still a useful way of categorising the design community by their outlook rather than by organisation size, specialisation or professional experience.

4. Conclusions and further work

This study has shown that representing products as a medium through which designers communicate with consumers can render an often difficult subject more comprehensible, not only to researchers, but also to designers and their clients. With respect to designer intent, designers *do form* distinct intentions for how their products should be perceived and thus strive to affect the consumer and stimulate consumption. However, designer intent is not the only determinant of product form and designers seek to maintain their intentions in spite of numerous conflicting constraints and potentially moderating influences. The form of the resulting product is therefore determined by a combination of the designers' intentions and the technical, commercial, logistical, personal and political pressures that they operate under.

By focussing this study on the visual form of products and the activities of industrial design consultants, the resulting interpretation is limited in its scope. Future work in this area might involve research to include other levels of product interaction (beyond the visual), other parties in the design process (beyond the designer and the client) and other design practices (beyond industrial design). Each of these potential expansions to the work would increase the richness of the interpretation and broaden the scope of any generalisations that can be made.

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IMPLICATION OF METACOGNITION IN DESIGN

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Abstract. Since their development, design methods have not gone unchallenged by either scientists or practitioners. Inappropriate use and poor understanding usually result in problems with acceptance and a lack of motivation to use design methods (Pahl and Beitz 1995). This phenomenon already becomes apparent at university level. At pmd in Darmstadt, an investigation using questionnaires showed that students who learn design methods are not motivated to use them if they do not see the purpose of the design method or the necessity of its application. This lack of understanding of design methods and their usability might be founded in aspects of cognitive psychology, metacognition in particular. The benefits of metacognition as a means of monitoring and controlling cognitive processes have been widely discussed in developmental psychology with regard to learning processes in school environments and education psychology (Trautner 1997; Seel 2003). On this basis the article explores aspects of metacognition with regard to design methods, their application and transfer to novice users.

1. Objective: Metacognition

In general, metacognition can be described as "knowing about knowing", which refers to the knowledge about one's own cognitive processes and the ability to control them (Metcalfe and Shimanura, 1994). There are basically three aspects of metacognition which need to be considered in this context: Meta-attention, metamemory and metaknowledge.

Meta-attention describes the ability to consciously control attention in order to select goal-oriented information.

The term metamemory refers to the mnemonic consciousness of a person. Various authors particularly stress the aspects of perceiving and accepting the limitations of one's own memory which helps a person to realize the need for strategies to overcome them (Trautner, 1997).

Metaknowledge is knowledge about knowledge, in particular, knowledge about the extent and organization of one's own knowledge. It includes knowledge about strategies, how to use these strategies efficiently and how to find new strategies.

The general benefit of metacognition is the promotion of controlled and goal-oriented cognitive processes. Trautner (1997) states that "the lack of knowledge about one's own cognitive processes is one possible reason for deficiencies in using strategies."

Metaknowledge is analyzed with special regard to the process of monitoring and controlling problem-solving behavior. According to Flavell (1979), metacognition is "keeping track of how it is going and taking appropriate measures whenever it needs to go differently".

Good problem-solvers dispose over an extensive metaknowledge. This becomes evident when they plan, observe, control and evaluate their own behavior and procedure. So, they are able to regulate their behavior in a flexible way according to the changes in the task (problem) and the context (Berliner 1994). Furthermore, they are able to assess the level of difficulty of a task and tackle possibly emerging problems. All these skills and abilities are required of a good designer (Pahl 1994).

According to the elements and characteristics of metacognition, the impact of metacognition for designing and teaching designing becomes evident. Metacognition supports a flexible and context-adapted problem-solving behavior, as it is observed by experts. Exactly this behavior is required when designing, dealing with complex problems and changing contexts. For this reason metacognition has a higher impact in design than in other disciplines.

With respect to strategic learning, engineering education could learn from clinical and educational psychology, where the method of inducing metacognitive mediation is accepted as a way to overcome learning problems or deficits in strategic reasoning in patients (Trautner, 1997; Friedrich and Mandl, 1992).

2. Methods

From the study of the relevant literature, key elements of metacognition which play an important role in engineering design were identified to serve as a basis for the analysis of design methods. Additionally, available literature related to metacognitive elements in engineering design was reviewed. It focuses mainly on retrospective reflection on the process (Badke-Schaub and Frankenberg 2004) which, however, is one specific aspect of metacognition Thus, it can be concluded that there is great potential for improvements of design methods and their teaching in investigating these elements and relating them to engineering design.

In a preliminary study, students in a design class were observed making their statements on the design process and the use of design methods.

Furthermore, metacognitive elements of teaching were integrated and the reaction of the students investigated.

3. Results

3.1. ANALYSIS OF TEACHING DESIGN

On the assumption that metacognition is essential when designing and is an important skill of designers students were observed in their design class. Students raised the three questions shown in table 1. The problems behind these statements are found in industry, as well (Birkhofer 2002), and are based in natural human problem-solving behavior (Anderson 1997).

TABLE 1. Typical statements and problems of design and design methods

Why do we have to use a design method? We can figure out a solution by ourselves.	Natural human problem-solving behavior is to stick with their own problem-solving strategies before accepting an external strategy or method.
Why do we have to repeat this working step? Why did we not know this before?	Humans dislike repeating working steps when solving problems (backward avoidance)
Our solution is working. Why should we check the requirement list again?	Naturally, humans take a dislike to their behavior and results being controlled.

These statements show that there is no metaknowledge yet. Metaknowledge and metacognition have to be learned and taught like other knowledge through certain teaching concepts (Collins et al. 1987; Hacker et al. 1998).

The lack of metacognition in these statements gives hints as to where teaching and training methods must intervene.

The first statement stresses the need for teaching efficient strategies and training students in developing their own strategies. This teaching and training have to include the essential elements of metacognition, in particular planning, observing and evaluation of one's own behavior in order to discover one's weaknesses and strengths as well as suitable strategies.

The second statement makes apparent the need for sensible explanations as to why iterations are useful and beneficial. Repeating and controlling things are strategies that good problem-solvers use in order to get better results. Therefore, one has to teach with explanations and practice the insights and understandings of the benefits of controlling and redoing working steps so that it results in a metacognitive strategy.

According to the third statement the awareness of the importance of controlling problem-solving has not been efficiently developed. It is a typical characteristic of experts disposing over a highly sophisticated metacognition. They also do an extensive analysis of the task. These are also metacognitive strategies which are gained through much experience and are memorized as metaknowledge. In order to teach them it is necessary to make students and designers aware of the importance of control processes. By analyzing the task in more detail and rechecking the requirements, the chance that one will choose an appropriate strategy and problem-solving behavior increases.

Therefore metacognition has to be taught in order to provide more insight into one's own abilities, the nature of the design process and the purpose of design methods.

3.2. ANALYSIS OF DESIGN METHODS

Design methods serve to support a purposeful and planned problem-solving strategy; thus, in controlling the process they act as external metacognition. By analyzing several design methods the elements of metacognition previously described can be identified.

Some design methods try to make the user step back and review the situation and his behavior (monitoring elements). So, VDI 2221 can be seen as a design method which helps keep an overview and have a reference for the whole process. VDI 2221 asks one to step back, monitor the process, and see in which phase one is working.

Other methods attempt to control the problem-solving procedure of the designer (controlling elements). VDI 2221 also has these elements, when it is asking to check the results of the single phases and check for weaknesses and lacks. Also the requirement list serves as a control element in order to collect and store all requirements.

The investigations detailed above show that design methods at least partially fulfill metacognitive functions. However, the elements acting as metacognitive control mechanisms are not explicitly verbalized within the design method descriptions. These facts promise to have a significant impact on the application as well as on the learning process of a design method. First investigations have shown that it is very effective if one explains and describes the cognitive effect and use of design methods in more detail. Students and designers are more motivated to use design methods if they know what they are for.

3.2. REQUIREMENTS OF METACOGNITION IN DESIGN METHODS

Since metaelements are not verbalized in design methods, they do not induce metacognitive activity in the designer and can consequently be mistaken for a corset which restricts creative problem-solving. Thus, design methods have two functions to fulfil; firstly, the organization of the design process and supporting the generation of a successful product. Secondly, they should support the designer in his/her cognitive functions, particularly in metacognition.

As a consequence, metaelements should be articulated clearly and incorporated into design methods. This could promote a more controlled and goal-oriented problem-solving behavior and thus yield better results in the design process.

3.3. THE CONTRIBUTION OF METACOGNITION IN TEACHING

By considering the role of metacognition in engineering education one can distinguish between two effects:

Metaelements, contained in design methods, can facilitate the learning process in that they can be directly applied even in the cognitive phase of skill acquisition. For this reason it is necessary to explicitly mention the metaelements in the design method in their descriptions and during teaching.

The other possibility to improve teaching is to create a general awareness of metacognitive processes, particularly by referring to the limitations of the cognitive system. Thus, explicit and scientifically founded explanations as to why students (as well as designers) need design methods and what their essential, or more specifically, their cognitive purpose is, could lead to greater acceptance of design methods and an increased motivation to learn them.

These two effects can be supported by teaching and training metacognitive learning strategies. According to Friedrich and Mandl (1992) there are four general metacognitive learning strategies which support metacognitive skills:

- Repeating strategy (active repetition of learning material)
- Elaboration strategy (links previous knowledge and new knowledge)
- Organization strategy (reduces the amount and complexity of information by structuring them)
- Controlling strategy (monitoring one’s own behavior and procedures)

These strategies have to be imparted and trained by teachers. In particular, self-observation and self-controlling have to be stressed, in order to induce a better adoption of problem-solving behavior. A teaching concept that integrates these strategies is Cognitive Apprenticeship (Collins et al. 1989). This concept particularly emphasizes self-verbalization and self-reflection as methods for discovering metacognitive strategies. This concept is based on problem-solving behavior in experts.

So, in a first step, it would be useful to perform small practical tests with students and designers in order to make them aware of certain cognitive limitations. In a second step, one has to show them how design methods can help them overcome these limitations. With this teaching approach one can better emphasize the use and benefit of design methods and make them more attractive to students and designers.

4. Key Conclusion and Outlook

This paper points out why metacognition plays such an important role within design and provides the opportunity to gain a better understanding of design methods, their functions and effects in particular. It also enables one to obtain greater insight into problems and failures in the application of design methods. After identifying elements of metacognition in design methods, the paper shows the chances of incorporating these elements in design methods and education. Based on these results, exemplary descriptions of design methods and an extended teaching concept will be developed and tested in a laboratory setting.

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CRITICAL POINTS FOR CHANGE

A vital mechanism for enhancing the conceptual design process.

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Abstract. Conceptual design is not a linear process; it consists of sub-processes, levels of refinement, which are individual but interact with each other. Each level of refinement corresponds to the types of media and tools used during conceptual design. Architects take advantage of a broad palette of tools and media for design, because each tool has its own strengths and weaknesses and provides an additional value—an added level of vision—to the architect. This closely relates to the notion of Critical Points for Change (CPC) a contribution this study makes towards a better understanding of the uniqueness of the conceptual design process. CPC are crucial moments when the architect suddenly becomes able to "see" something which drives him to go back and either alter his idea and refine it or reject it and pursue a new one. They are crucial parts of the design process because they are a vital mechanism for enhancing design. This characteristic of the nature of the conceptual design process is independent of the tools. Nevertheless, the right tools play an extremely important role. The distinctive capabilities of each tool allow the architect to deal successfully with CPC and overcome the points in the design process where he or she feels "stuck." Four Case Studies on practicing architects and a Survey on Tools for Conceptual Design conducted among architects provide valuable background material and support the arguments of this study.

1. Introduction

A massive volume of research has focused on trying to understand how designers perform design. Researchers have approached the exploration of design activity through different research methods, including protocol studies, interviews, and simulation trials. They all agree on the importance of the sketch as the primary tool for developing design concepts, stimulating thinking, performing design reasoning activities, and facilitating the architect's conversations with himself and others.

2. Conceptual Design Process

The design process is open-ended and problems and solutions cannot be clearly identified and separated. This set of problems and solutions cannot be broken into parts that can be solved separately; it has to be treated as a whole. Moreover, there is no perfect, “right,” solution, only preferred, better ones. During the hunt for a better solution there are often back and forths, switches between different media and tools, and constant questioning of ideas through comparisons, tests, and rejections. The conceptual design process is not linear.

Since there is no one “right” solution, but only better ones, there is also no panacea or set of methodologies for approaching conceptual design. As one of the case studies reveals, an architect can use different strategies in every project and cannot prescribe which the right one is. For example, Bernard Tschumi believes that in some projects computer tools are crucial in helping develop the concept (Museum of Sao Paolo) and on some others not at all (New Acropolis Museum). Similarly, in an other case study of the same research, we can distinguish the different approaches that each of the four architects followed, as they prioritized the structure, the function, the form, or the concept.

Furthermore, according to the data gathered from 242 architects who participated in the Survey for Tools for Conceptual Design, most of them tend to explore two to three ideas before they choose the “one” and move on to design development. What is interesting is that, contrary to what one would expect, the more experienced someone is, the fewer ideas he/she tends to explore. In fact, the Survey reveals that senior architects tend to explore fewer ideas than the drafters or interns in offices (Fig. 1).

Also, contrary to common logic, exploring more ideas does not necessarily mean that conceptual design takes a larger proportion of the total design time: architects who explore four to five ideas spend less time on conceptual design than those who explore two to three ideas. However, no matter how many ideas the architects explore, they do often feel the need to go back and revise their design.

In addition, switching between different media and tools creates loss and duplication of information and forces them to re-enter information; nevertheless, they choose to do it even if that causes delays.

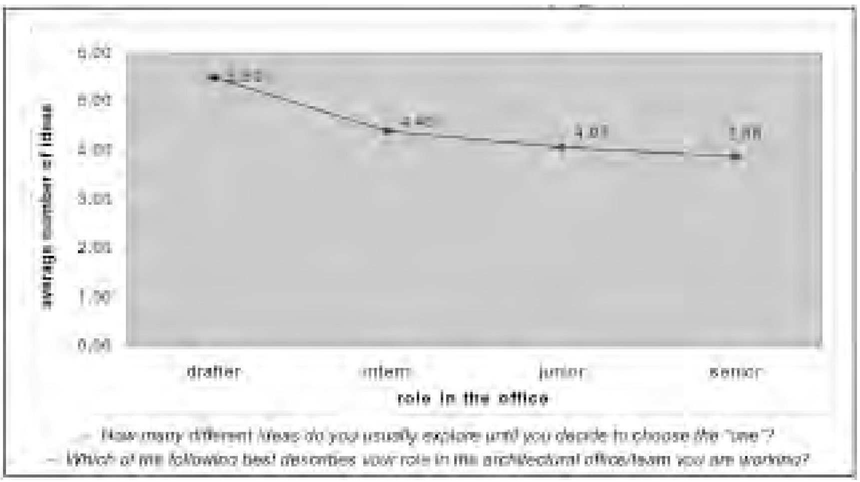

Figure 1: The more experienced an architect is, the fewer ideas he/she tends to explore

3. Comparative Method

One of the most common practices in conceptual design is the comparative method. The architect creates many alternatives in order to be able to compare, reject, and select. It is easier for the human mind to select one solution among others than to conceive of it originally and directly. This preference is similar to the following problem: when given a straight line and asked to mark an eighth of its length, it is easier to divide it in half, then divide the remaining length in half and the remainder in half again. The mind works better when comparing than when calculating.

Marples argues that the nature of a design problem can only be discovered through examining proposed solutions (Marples, 1961). He argues that if we examine only one proposal we end up with a very biased view. We need at least two radically different solutions in order to compare them and get a clear picture of the "real nature" of the problem. Nigel Cross agrees that even a conjectured solution is critical because it helps the architect understand the design problem. Generating a variety of solutions is a method of problem analysis (Cross, 1990). Hand drawn sketches have traditionally been the primary tool for design exploration and experimentation. Sketches not only allow the architect to vizualize his or her thoughts; they also provide valuable feedback and facilitate a constructive dialogue between the architect and his or her ideas. John Gero stresses the importance of hand drawn sketches as a means of review: architects generate more meanings when revising their sketches than when drawing them (Gero et al., 2001). Architects have recently discovered the potential that certain

computational tools have in helping them "talk" with their designs, in order to explore, play, be surprised, get inspired, meet the unexpected, judge, compare, refine, reject and select.
A tool for conceptual design must facilitate the need for comparisons, as an essential element of design thinking, design reasoning, and problem solving.

4. Sub Processes - Levels of Refinement

Conceptual design is not a linear process. It consists of sub-processes which are individual but interact with each other. Each sub-process has its own unique value and grants the architect an additional level of vision. The sub-processes correspond to the types of media and tools used during conceptual design.

For example, in one of the Case Studies of my doctoral research we can distinguish four separate sub-processes, which play a valuable role during decision making:

a) Sketching,
b) 2D CAD,
c) 3D digital modeling, and
d) 3D physical modeling (Fig. 2).

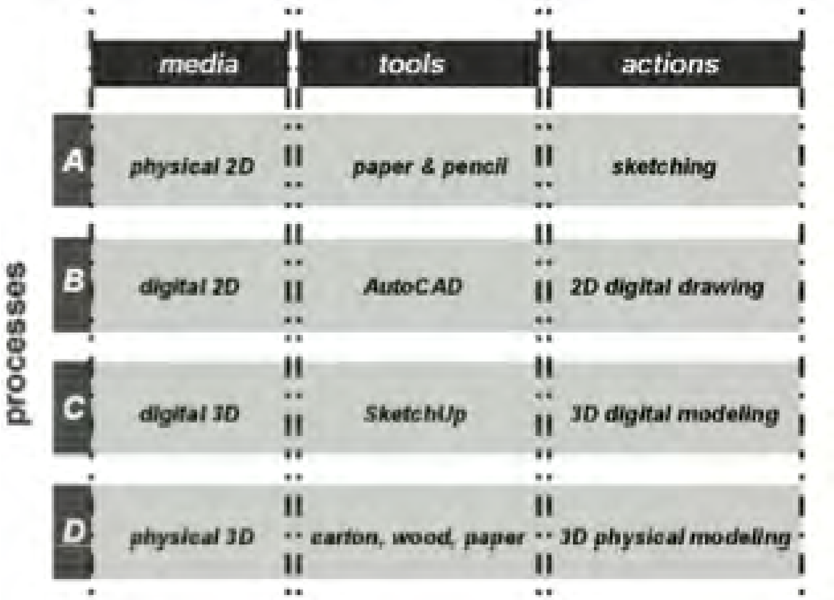

Figure 2. Example of the four Sub-Processes observed at one of the Case Studies.

In this example, only when the architects used a digital 3D model were they able to see an aspect of the design –which sketches and 2D CAD could not reveal- and decide that they had to go back and change the main idea. Going back entails a manual update of the design with new sketches and new CAD drawings. Similarly, only when the architects built a physical 3D model were they able to see another aspect of their design that needed to be altered; they decided to go back again and make the appropriate changes. Then again they had to re-input information in new CAD drawings, a new digital 3D model, and new sketches (Fig. 3).

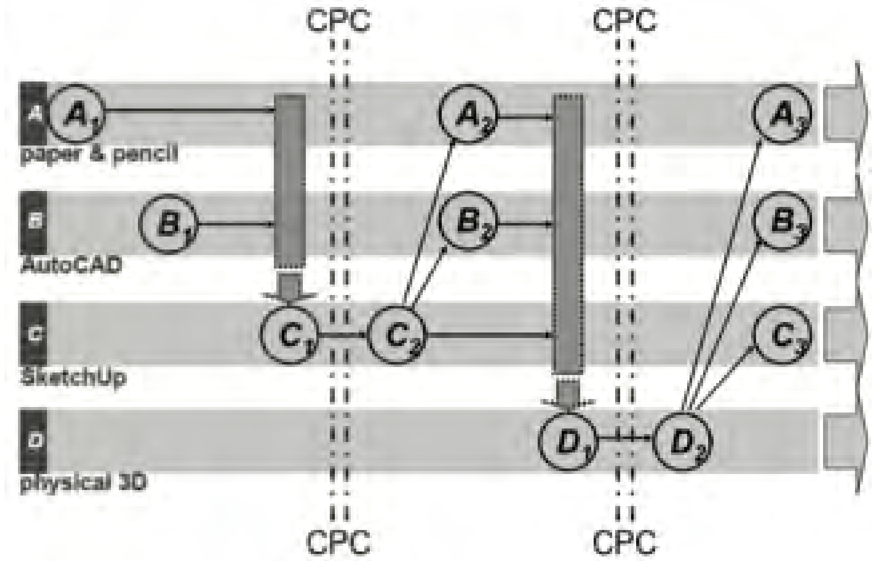

Figure 3. Critical Points for Change occur when the designer becomes able to "see" something that drives him to go back and alter his idea or start with a new one.

These sub-processes operate as levels of refinement for the conceptual design process. Each level functions as a filter for narrowing down the number of alternatives to be explored. The architect begins with a large number of alternatives and at each level confines the choices until it is possible to choose the most preferred one, which then goes on to design development.

5. Critical Points for Change

The levels of refinement are closely interrelated to the notion of *Critical Points for Change*. These are moments when the architect "sees" something that drives him to go back and either alter his idea or start with a new one. They are crucial parts of the design process because they are a vital mechanism for enhancing design. They either trigger alterations that refine the design solution or provoke the architect to reject the idea and pursue a better one.

Often a new level of refinement would provoke a CPC. Through the help of a new tool, the architect becomes able to "see" something that was not visible before and can decide to go back and a) alter the design idea, b) abandon it and begin from scratch, or c) abandon it and pick an idea that had been discarded or left "inactive". The Case Studies that supplement my doctoral research demonstrate examples where CPC occurred on real projects. Moreover half of the architects who participated in the Survey on Tools for Conceptual Design reported that several times they had changed their minds and that they went back even if they had proceeded to the design development stage.

Even though CPC might look like irregularities that make the conceptual design process inefficient, the truth is that they are absolutely necessary for a creative, genuine course of design exploration. Besides, the desired outcome does not emerge on the first try. Architects need to explore a number of ideas until they can choose the optimal one. The Survey on Tools for Conceptual Design reveals that less than one percent of the architects explore only one idea: 40% explore two to three ideas, 32% explore four to five ideas and 27% explore more than six ideas until they decide to choose the "one".

Tools for conceptual design should not attempt to disguise or underestimate the Critical Points for Change. To the contrary, the tools should assist the architect during CPC cases in six ways:

a. Reveal CPC cases earlier in the process.
b. Provoke the emergence of more CPC cases.
c. Encourage deeper exploration of each alternative by offering additional levels of vision and understanding.
d. Support the architect in the dilemma of whether to alter an idea or abandon it and start again from scratch.
e. Organize all the different ideas and present a broad palette of them.
f. Integrate the different media and tools in order to reduce the inefficiencies that CPC causes.

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MODELLING DESIGN E-LEARNING ENVIRONMENTS THROUGH DESIGNERS OBSERVATION

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Abstract. It's a common experience that the manner in which designers tackle their design problems depends very strongly on the problem they see. The consequent situated nature design is one of the most challenging features, making general design taxonomies hard to formulate. Technology enhanced design learning and design studies share the effort of understanding situated design processes, so that models of design and systems for design learning can be defined. The objective of this research is to develop a set of requirements for advanced design learning environments. This paper reports on a protocol analysis of a number of students' homework review sessions in regular university classrooms, and draws some evidence of the relationships occurring between conceptual and visual reasoning in Architectural Design.

1. The Reference Model of Design

Understanding reality through observation is always guided by a set of assumed models which restrict the universe of event to a coherent subset of relevant ones. These models, assumed in advance in order to guide observation, are then assessed or certified by the degree of coherence they provide in the explanation of the observed phenomena (Johnson-Laird 1999).

In addition, understanding the design "phenomenon" requires the assumption of a set of models that can effectively guide the observation procedures. This work uses a structured set of design models, consisting in a meta-model, which describes the general strategy of design and a cognitive model which renders the meta-strategy operational, by identifying well defined cognitive actions. The meta-model is based on the conception of underdetermined design problems (Dorst 2003). Design problems are only partly determined by needs, requirements and intentions. Underdetermined problems do not provide enough information with which to build a complete design space. Rather, problem spaces definition and problem solving flow concurrently, through the exploration of possibilities and problem (re-)

interpretation. This process is usually called co-evolution, its goal is to arrive at a matching problem-solution pair (figure 1). As a consequence, the design problem space is not stable and the only relevant problems are the one the designer sees.

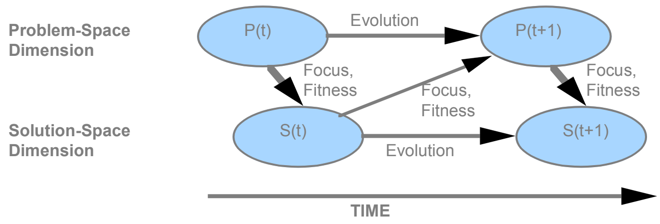


Figure 1 – Co-evolution of problem and solution spaces

Multimodal perceptual representation and diagrammatic reasoning (Chandrasekaran 1999) outlines a view of "cognitive state" as an integrated and interlinked collection of "images" in various modalities: the perceptual ones, and the kinaesthetic and conceptual modalities. Thinking, problem solving, reasoning, etc. are best viewed as sequences of such states, where there is no intrinsically preferred mode. So perception and imagination are deeply related processes that make use of internal representations called *mental images*. The external world, at various points, contributes elements to one mode or another. Our implementation of multimodal perceptual representation is depicted in figure 2. Human cognitive faculties have been modelled as a computational framework consisting in a working memory and a long term memory. Information is represented according to two main types:

- Logical structures: relatively fine grained and almost loosely coupled fragments of knowledge, whose processing is guided mainly by conscious inferences and strategic plans;
- Mental images: sets of percepts that are arranged according to schemata that are relatively fixed, whose processing is mainly unconscious.

Mental images can be aggregated to form more complex patterns and/or abstracted to produce their logical interpretation. Mental images can also be reflected on external media (e.g. sketches on paper) and reinterpreted. Mental models are representation frames that aggregate sets of logical structures and the related mental images and characterize significant portions of the reality.

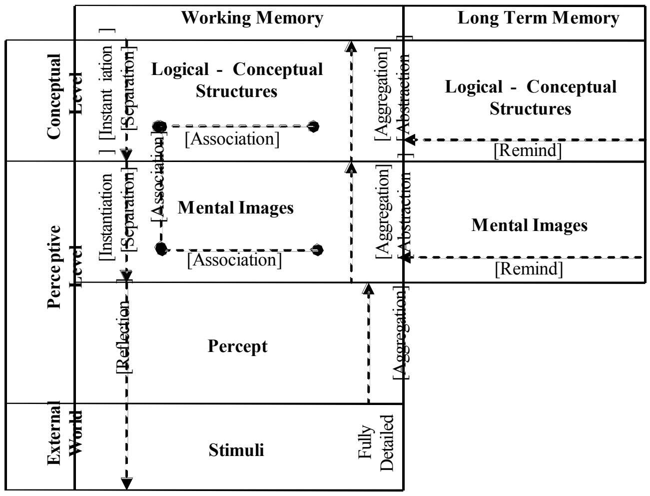


Figure 2 – The simplified implementation of a multimodal perceptual design reasoning model. Arrows represent inferences occurring between different models or within the same modality.

3. Methodology

The protocol analysis setup was applied to the homework review sessions of 10 students in a regular course, during the last year Architecture-Engineering Degree at Università Politecnica delle Marche, Italy. The approach had the unique feature: embed a design oriented LMS into the traditional design studio practice of students' homework reviewing. Homework design revision, made public in this way (see figure 3), became a privileged event recording the objectified verbalization of design thought. The LMS provided a large amount of traditional e-learning course paragraphs containing both theoretical lessons and design cases, arranged either according to a traditional syllabus in 23 courses, and according to 23 different ontology's indexing paragraphs contents through semantic nets. Fostering the association of concepts and images, and allowing for sketching on every sort of materials, this apparatus suited our purpose as it supported access to conceptual and visual information at different degrees of abstraction and structure (texts, photos, drawing, sketches, cases, etc.). The coding schema was defined by adapting a previous knowledge level protocol analysis technique (De Grassi 1999) (Gero 1998) in order to trace the evolution of multimodal perceptual representations. The resulting schema provided traces of the design though as it is shown in Table 1.

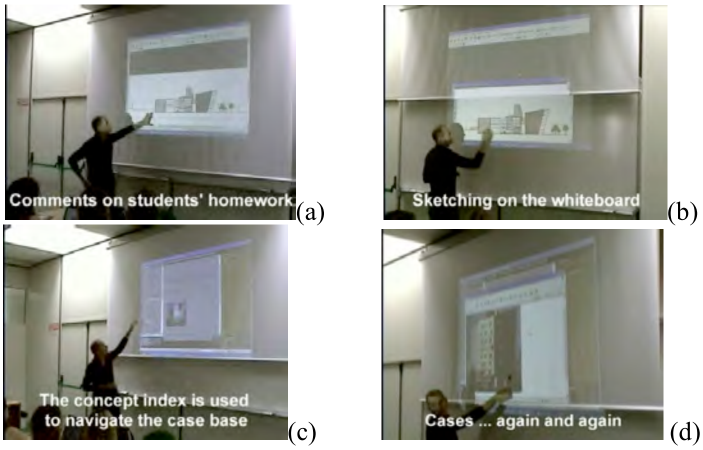


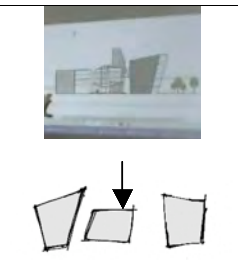
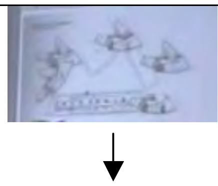
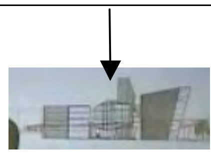
Figure 3 – An LMS assisted homework design revision.(a) Comments on students' homework. (b) Sketching on the student's drawing.(c) Case searched through the ontology sub-system (d) Analysis of design cases.

4. Results

The elaboration of the results of this work is still in progress but, already, some interesting aspects can be discussed. The co-evolution model is evident at the macro-strategy level of every design trace we have recorded. A great percentage of the design work, especially in the early stages, consists in constructing the design space. This construction is mostly made by aggregating design issues on the basis of their reciprocal relevance. This appears to be the key relation that glues the different chunks of the design space. This relation is derived either from previous cases or from models, depending on the particular phase of design (ideation, detailing, etc.). The case based design cycle is also well shown in the micro-strategy column and it is directly reflected in the teacher's activity column. The [indexing] micro-strategy sometimes does not appear directly. Our guess is that in that case it is performed unconsciously. A weaker evidence of the existence of an indexing mechanism usually appears on later speech transcripts, when the teacher comments the recalled case. Regarding the multimodal perceptual representation model, we observed that associative thought appears to be the main type of reasoning. Associations link both concepts and images. These are almost instantaneous and aren't reflected in any verbal transcript before they occur. After an association occurred some explanation usually took place, consuming a significant amount of time. This leads us to hypothesize that associations are mostly "hard coded" in teachers' mind and that explanations are built through explicit inferences. To this concern, it's worth noticing that teachers' explanations are never the same - even on the same subjects.

Semantically far associations usually open new and unexpected design subspaces (creativity?). The use of the LMS system, as a large associative memory, sometime moved the design flow to subspaces that the teacher did not consider relevant at the moment. But the visual impact of the recalled case image often stimulated new reflections and analysis leading to unexpected solutions. The same thing happens within the sketching process by means of the [reflection] mechanism. This lets us argue some evidence of the multimodal perceptual representation model. Because they usually do not drive the abstraction of new concepts, mental images appear to be just vague representations of the visual stimuli. Mental processing on recalled images seems to move only on existing knowledge structures, in other words, only the presence of fully detailed external stimuli (e.g. pictures, drawing, sounds, etc.) triggers the development of new abstract representations. Visual diagrammatic (schematic) representations play a very important role in the overall design process. They arrange images into classes and bridge the image level and the conceptual level through a codification of percepts that abstract from unnecessary details and focus on few and semantically well defined features. Coding is performed at the level of visual images; therefore diagrammatic representations keep the same spatial expressive power of fully featured pictures (they can be translated, scaled, stretched, etc.). At the same time, they are so simplified that their description into words is made agile. To this aim, it is worth noting that teachers, describing fully featured pictures, usually adopt words with a very high degree of figurative content, like "crystal", "pivot", etc. However, when they talk about diagrammatic representations, more neutral words such as "volume", "space", etc. are used. In the first case, the enriched wording is used to compensate the lack of diagrammatic interpretation. In the second case, words are just pointers to already well qualified spatial regions.

TABLE 1 – Example of a coding schema. Macro strategies are defined in terms of the co-evolution model. Micro strategies are defined in terms of multimodal perceptual representations. Knowledge contains the transformations caused by the micro strategy. Act contains a description of the teacher's actions. Activity outcome is the record of the teacher's action.

T	Macro Strategy	Micro Strategy	Knowledge	Act.	Activity Outcome
0'33''	Problem position	[Abstraction] from image stimulus to visual schema		Comment on student's drawings	This design doesn't show a **hierarchy among its parts** keeping them together
0'53					This design law must be evident in every prospect view
1'00''					In your work I read three elements that are not well coordinated
1'10''	Problem solution	[Indexing] Qualification of student's design elements	High rising Crystals 	Recall of a Reference Case	(*No evidence indexing keys are hypothesized from later words*)
1'20''		Analogical [Remind]	 Zaha Adid - Berlin		A useful reference is the Adid project in Berlin
1'50''		[Abstraction] from image stimulus to visual mental diagram			The formal quality of the **high rising element** depends on the existence of a "**shoulder**" that points out its **pivot** or **crystal**. role
2'30''		[Reflection] Adaptation of the mental diagram to the student's design context		Sketch on the student's drawing	In your case, we read only detached elements. We need to glue them with a coordinating element that implements the design hierarchy. 
3'40''	Problem Position (Expansion of the design space)	[Association] The "lightness" issue is derived from the Adid case since it is a relevant feature of this design.			
…	…	…	…	…	…

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EXPLORING THE EFFECTS OF INTRODUCING REAL-TIME SIMULATION ON COLLABORATIVE URBAN DESIGN IN AUGMENTED REALITY

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Abstract. We report a study using ARTHUR, an augmented reality system in which simulated pedestrians (agents) interact with design proposals during architectural design and urban planning. We looked at the effects of the agents on how designers used the system. We found that the simulation encouraged complex integration of design and review which took the designers in unexpected directions. It also reduced the extent that participants 'envisioned'. Participants used the agents in many 'design experiments', but unexpected agent behaviour could be frustrating, creating a tendency for subjects to block or corral agents (rather than create opportunities). We discuss our findings.

1. Introduction

As a design-support technology, augmented reality (AR) offers impressive possibilities for designers. Using AR, three dimensional models can appear as if on a physical meeting table. These can then be collaboratively developed in ways that would be impossible with a physical model. A further possibility is to run computational simulations of complex, real-world phenomena on a model whilst designers simultaneously explore design possibilities. The potential benefits of these possibilities has resulted in research projects exploring AR to support common-view, collaborative manipulation for architectural design and urban planning in combination with 3D computational simulations (for example, URP (Underkoffler & Ishii, 1992) and MousHaus Table (Huang, Yi-Luen Do, & Gross 2003)). Studies of people using such systems can reveal how these new possibilities affect design processes, as well as providing a source of reflection on the nature of design (Gero *et al*., 2004) and how systems might be effectively deployed. So far little work has explored what these affects might be.

We report a study of ARTHUR (Fatah gen. Schieck et al., 2005), an Augmented Reality system that enables designers to work together, while simulated pedestrians interact with their design. The study explored how a real-time simulation of limited complexity viewed from a 'God's eye' perspective in AR would affect the way users with architectural and urban design experience approached design problems. In subsequent sections we describe ARTHUR as configured for the study and the study methodology. We then report and discuss our findings.

2. System Overview

ARTHUR supports collaboration in architectural and urban design review sessions by projecting a virtual model onto a real round table. The model can be viewed by multiple users using see-through AR glasses. A pedestrian simulation allows the consequences of design changes to be evaluated while the design is being manipulated. Figure 1 shows how the model looked for one subject during the study. The dominant grey area represents a city square surrounded by buildings. Objects in the square represent street furniture and amenities including market stalls (blue striped canopies), two tube exits (top left, bottom right), a toilet (top right), and a play area (bottom left). Simulated pedestrians (agents) appear as red domino-shaped blocks.

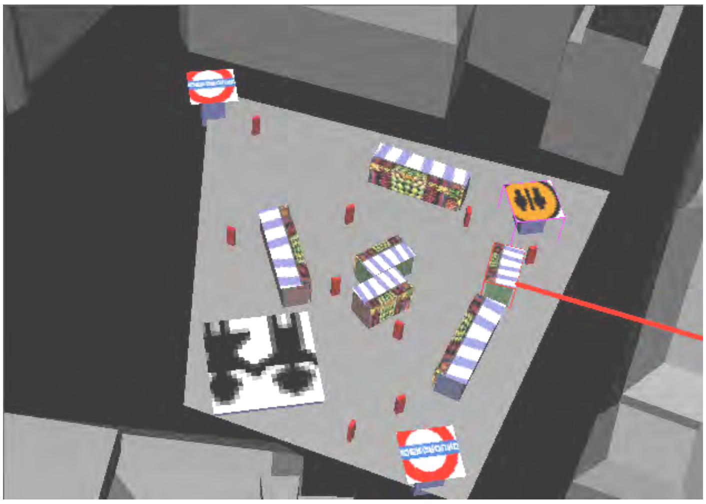

Figure 1: A view of the market square using ARTHUR.

For the current study, manipulation of virtual objects was supported using modified mice (one per user) which were mapped to pointers in the virtual world (shown as a continuous red line in figure 1). Using a pointer users could:

- select objects (pointing and clicking the left mouse button);
- move objects in the XZ plane (moving the mouse in the XZ plane when an object is selected); and
- rotate objects (selecting an object and rotating the mouse around the Y axis).

Agent movement was based on a combination of exploratory and goal-directed behaviour. In the model, the underground exits and the toilet acted as entrance/exits. At each step, an agent would judge the longest line-of-sight within its field of vision and turn towards it. After ten steps, if an exit fell into view the agent would move towards it and exit the model.

3. Method

12 postgraduate students and researchers in architecture and urban planning at UCL, London were given an initial training session with ARTHUR before working in pairs to perform two market design tasks in a cross-over study design. The first task phase was designated ‘July’ and the second ‘August’. For comparison, each task was first performed without and then with pedestrian simulation (4 trials in all). Each trial required subjects to arrange market stalls into a ‘good’ design around the remaining amenities (fixed). No time-limit was imposed.

Post-task debrief interviews were used to identify emergent themes prior to an analysis of subjects’ dialogues using summarised narratives and coding of conversational ‘turns’ (agreed by two independent coders). A combination of qualitative and quantitative analysis was performed as described in the next section.

4. Findings

4.1 PEDESTRIAN SIMULATION PROMOTING PEDESTRIAN FOCUS

During post-task interviews, subjects reported that the extent to which they considered pedestrians was not increased by the simulation, but the way they considered pedestrians had changed. They considered that their priorities changed towards promoting the extent to which agents visited market stalls. In fact, there was a significant increase in discussion about pedestrian between *without* and *with* agents conditions (one-tailed Wilcoxons, $p < 0.05$). There was no difference between the ‘no agent’ conditions before and after simulation.

4.2 RELATING TO AGENTS

Following subjects’ reports that the simulation changed how they considered pedestrians, an exploratory analysis was performed of how this may have been revealed in subjects’ conversations during the trials. This showed that before the simulation, subjects described pedestrian behaviour and experience in both the third-person (*e.g.* '*they* can also buy something from the market'), and the second-person (*e.g.* 'if *you* get off the train, *you* can see…'). When agents were introduced, use of the second-person reduced considerably and only increased a small amount in subsequent trials.

Another aspect of subjects relating to agents revealed by the dialogues was that they often made inferences about its underlying basis. This was done either in terms of how the system might have been 'programmed', or by hypothesising about the agents' mental lives. For example,

S1b: Erm… the agents are very slow aren't they?

S1a: They just want their time.

S1b: I see what they're trying to do…

4.3 INITIAL DESIGN CONCEPTS AND REFLECTIVE ACTION

At the start of each trial, subjects almost always agreed a broad design idea. This idea (apparently corresponding to Darke's (1978) Primary Generator) either prioritised an abstract form (*e.g.* a 'street' or a 'square') or specific properties (*e.g.* access or visibility). In the second run (with simulation) of each problem, the primary concept was to recreate the previous solution as a starting point. Five of the six groups explicitly conducted such 'experiments'. Moreover, all pairs explicitly reflected on agent behaviour in evaluating their prior designs.

4.4 USING DESIGN TO CONTROL BEHAVIOUR

The longer participants worked with the agents, the more agent behaviour could appear odd or even frustrating. The agents did not necessarily interact with the markets as the designers intended (In the simulation, stalls were not 'attractors', and were only visited through chance encounters).

The agents' apparent lack of interest in the stalls frequently led the designers to refocus their efforts towards encouraging agents toward the stalls. Where subjects previously talked about creating space, they now repositioned market stalls and sometimes used them to corral movement. Every subject pair explicitly used the stalls to direct agents at some point, and directing pedestrians (or proxies) was discussed 23 times in total, 17 of these being during agent simulation.

This refocusing of design goals tended to divert attention from, or compromise, the primary design concepts. Two pairs dropped their initial design concepts entirely and focused on getting agents to behave acceptably. When agents were introduced, two pairs began by focusing on agent behaviour before reflecting, and reverting to more abstract design principles. Five of the six pairs made explicit the tension between designing 'well' (or simply "designing") and getting agents to behave desirably.

4.5 ANALYSIS OF SOLUTIONS

An analysis was performed to see whether the shift in priorities towards visiting stalls translated into measurable differences in design solutions. Pedestrian simulations were run on all trial solutions (10 agents for 1000 agent ‘steps’) with movement mapped to cell counts in a superimposed grid.

Stall front and rear proximity figures were calculated as the total steps occurring within a one-stall-area. The results, summarised in figure 2, show a steady increase in front of stall visits across trials and a general decrease in rear of stall visits. This supports the idea that subjects worked to increase front-of-stall visits, decrease rear-of-stall visits and that performance generally improved across trials.

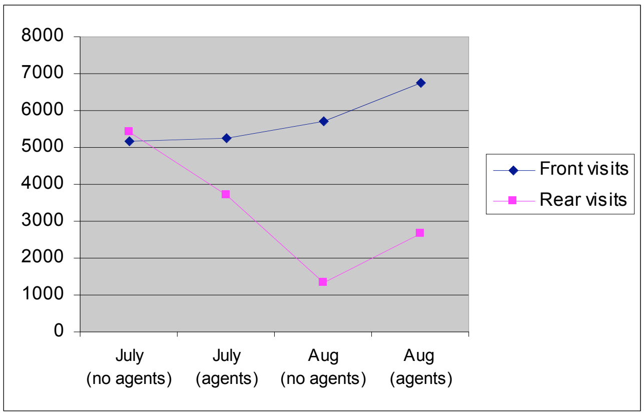

Figure 2. Total front and rear stall visits across all subject pairs for each trial.

5. Discussion

Although increased discussion about pedestrians during simulation did not persist post-simulation, the increase in stall-front visits and the more pronounced decrease in stall-rear visits demonstrates a developing interest and ability to address the agent behaviour as presenting new requirements. The agent simulation influenced design by informing local and global experiments, including the use of agents to debug previous design ideas. The simulation encouraged an integration of design and review which took the designers in unexpected directions.

The contrast the simulation created between expectation and observation is perhaps attributable to simplicity in the simulation, but if real-time simulations are of value in design, then it is only where they force designers to think more deeply about the implications of design on behaviour. In the current study, the ‘idealised’ design concepts and a presented ‘reality’ often appeared incompatible. The higher-level concepts may well have been supported by visions of pedestrian behaviour, but when the simulation diverged from these, the initial concepts were stretched and sometimes dropped altogether.

The reduction in second-person speech suggests the agents encouraged a more objective perspective. Subjects no-longer invited their partners to experience the pedestrian experience. Perhaps the mental transformation in perspective necessary for an imagined walkthrough became problematic during the visual 'noise' of simulation. Perhaps subjects considered such walkthroughs unnecessary in the face of observed behaviour.

Whichever the case, interacting with the simulation appeared to make the designers less empathic, tending more towards 'crowd control' than designing an experience. This objective point of view is potentially an asset where aggregated movement is a prominent concern, but it may also need to be balanced with first-person perspective walkthroughs for subjective evaluation.

Designing three dimensional models with real-time simulation through AR has the potential for adding value to urban planning and architectural design by revealing behaviours to designers early in the design process, and providing an objective source of reflection. This, and some particular effects of such simulations, have been demonstrated in this study. In conclusion, the study raises questions we hope to address in future work. It raises questions about sophistication and variation in simulated behaviours (goals and context) and how this might influence the trade-off between design 'ideals' and design 'reality'. It also raises questions about designers' empathy with users of their designs and how this is affected by first-person perspective walkthroughs as a complement to 'Gods eye' observations of autonomous activity.

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ARCHITECTURE DESIGN INTELLIGENCES

A case for Multiple Intelligences in Architectural Design

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Abstract. The main premise of the study is that architects are intelligent insofar they can use multiple abilities in architecture design tasks. *Design intelligence* is hence defined as the array of abilities & skills intentionally used by architects for achieving desired goals in a specific environment. The author attempts to investigate how architects use their intelligences in specific design tasks using Multiple Intelligence theory of Howard Gardener in an ongoing dissertation study by reviewing an undergraduate studio at the School of Architecture and Urban Planning, University of Wisconsin-Milwaukee. Findings are anticipated to have larger implications on multiple performance criteria in teaching and learning, the creation of multidisciplinary studio models, and as a framework for evaluative and diagnostic design assessments in architecture design and computation.

1. The Need for the study of Architecture Design Intelligences

The complexity of architectural design tasks requires individuals who possess a wide array of abilities (such as spatial visualization, logical thinking, problem solving skills, linguistic ability, communication skills and so on). Yet architectural pedagogy and practice continue to focus on limited areas of inquiry such as *formal logic* - which is still the prevailing discourse in design studios. Validity of diverse approaches in architecture have profound implications to multidisciplinary studio models (Groat & Ahrentzen, 2001), for assessing multiple performance criteria in teaching (see 37 performance criteria determined by NAAB, 2005), and a framework for architectural aptitude tests in education and practice. The main premise of the study is that architects are intelligent insofar they can use multiple abilities in architecture design tasks. *Design Intelligence* is defined as the array of abilities & skills intentionally used by architects for achieving desired goals in a specific environment.

Yet, the available instruments in measuring design intelligences are limited in capturing the complexity of architectural tasks because they are usually borrowed from psychometric studies (Mackinnon, 1978, Newland et al, 1987) that usually test universal abilities. Moreover, these tests are decontextualized from the naturalized setting of architectural design tasks. Given these deficits, the current study aims to examine design abilities through the multiple intelligence theory of Gardener (1983) and the domain-field-interaction model of Feldman et al (1994). Two kinds of instruments are used. An in-depth protocol study lasting one semester and the ADIAS (Architecture Design Intelligence Assessment Scale) survey questionnaire developed by the author (D'souza,2004). Both these instruments are based on Multiple Intelligence Development Assessment Scale (MIDAS) developed by Shearer (1999) to assess Multiple Intelligence theory of Gardener. Three different design tasks are examined in a design studio study lasting four months and the following questions are tackled: Which intelligence(s) do architecture students excel in? How do students use intelligences in their design process? Whether students use intelligences in isolation or as a nesting of multiple intelligences? Is there diversity among students in their priority of using Multiple Intelligences? How much of multiple intelligences is related to design task v/s inherent abilities? and To what extent can multiple intelligences be used as a diagnostic tool?

2. The Potential of Gardener's MI theory for understanding Architectural Design Intelligences

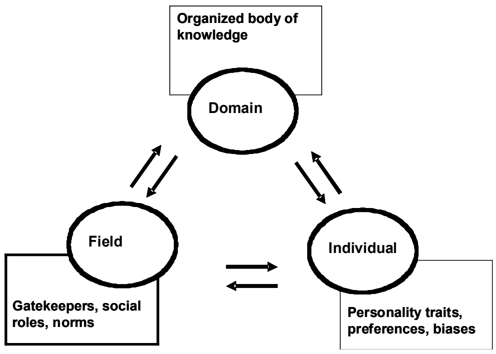
Howard Gardner's Multiple Intelligence theory was first published in his book, *Frames Of Mind* (1983) and was influenced mainly by his study on cognitive problems in people suffering brain damage in Boston medical school. The MI theory soon became an accepted model in educational circles because of its appeal to multiple abilities in an education system which relied mainly on specific achievement tests up till then. According to Gardner there are eight forms of intelligences. These include *verbal, logical-mathematical, spatial, bodily/kinesthetic, musical, interpersonal, intrapersonal* and *naturalistic intelligences* (Table 1). Besides conforming to multiple abilities, Gardener also suggests that rather than a universal model unaffected by context, intelligences should be defined as the ability to solve problems or fashion products that are valuable in one or more cultural settings. What this means is an implied interaction between individual abilities as well as the cultural setting one operates in. Since the process and products of architecture are to an extent culture & context specific, an interaction model that includes individual abilities and specificity of a design task is useful. Such an interaction model has been elaborated by Gardener and colleagues in terms of *Domain-Individual-Field* Interaction model, Figure 1.

TABLE 1. Multiple Intelligences and their characteristics (Gardener, 1983)

INTELLIGENCE TYPE	FEATURES
(i) Verbal/Linguistic	A person with verbal intelligence is sensitive to meaning and order of words. Verbal intelligence involve excellence in activities such as hearing, listening, impromptu or formal speaking, tongue twisters, humor, oral or silent reading, documentation, creative writing, spelling, journal and poetry. Personalities associated with verbal intelligence are poets and journalists.
(ii) Logical-mathematical	A person with logical-mathematical intelligence is able to handle chains of reasoning and recognize patterns, numbering and order. Logical-mathematical intelligence involves excellence in activities such as understanding abstract symbols/formulae, deciphering codes, numerical calculations and problem solving. Personalities associated with logical intelligence are mathematicians and computer programmers.
(iii) Musical	A person with musical intelligence is sensitive to pitch, melody, rhythm, and tone. Musical Intelligence involves excellence in activities such as musical recitals, singing on key and musical compositions. Personalities associated with musical intelligences are composers and conductors.
(iv) Spatial	A person with spatial intelligence can perceive, transform and modify spatial information easily. Spatial intelligence involves excellence in activities such as recreation of images, drawings, sculptures, forms, color schemes and so on. Personalities associated with spatial intelligences are artists, painters and sailors.
(v) Bodily-kinesthetic	A person with bodily-Kinesthetic intelligence is able to use the body, has control over motor actions and the ability to manipulate external objects. Bodily-kinesthetic intelligence involves excellence in activities such as drama, role playing, sports and dancing.
(vi) Intrapersonal	A person with intrapersonal intelligence has the ability to recognize personal feelings and emotions. Interpersonal intelligence involves excellence in activities such as silent reflection, concentration skills and higher order reasoning. Personalities associated with Intrapersonal intelligences are writers and thinkers.
(vii) Interpersonal	A person with interpersonal intelligence has the ability to recognize others feelings, beliefs and intentions and understand people and relationships. Interpersonal intelligence involves excellence in activities such as group projects, counseling and feedback. Personalities associated with Inter personal intelligences are counselors , human resource personnel and teachers.
(viii) Naturalistic	A person with natural intelligence is able to connect with the intricacies and subtleties of nature. Naturalistic intelligence involves excellence in activities such as archeology, paleontology and wildlife watching. Personalities associated with naturalistic intelligences are botanists and archeologists.

The interaction of the domain, individual and field could be fully appreciated in the context of a architectural design task. For example in a museum design, the *domain* (which is the organized body of knowledge) could consist of precedents that focus on visual or formal typologies. The *field* (which is the social aspects) could consist of issues such as viewing the museum as an object that is used and consumed by the society as a whole. The field could also consist of gatekeepers who are relatively well known for their artistic qualities (e.g. Meir, Calatrava etc.) rather than architects known for their functional or programmatic ideas. Finally, the *individuals* required for the design of a museum may need abilities such as spatial visualization, sensitivity to movement/light and so on. The important implication of this model is that the level of intelligences in a given place at a given time does not depend only on the amount of individual abilities alone. It depends just as much on how well suited respective domains and fields are to the recognition and diffusion of intelligences.

Figure 1. The Domain-Individual-Field Interaction model of Feldman et al (1994)



3. Defining Architectural Design tasks: The 410 studio at SARUP

The 410 architecture design studio at SARUP (School of Architecture & Urban Planning), University of Wisconsin-Milwaukee, provides an opportunity to understand multiple intelligences in a rigorous manner. This studio sequence typically consists of three design problems and is developed as a preparation for professional architectural practice, with emphasis on analysis of information, definition of architectural objectives, formation of logical design methods, and presentation of coherent ideas. They include three building types: (i) The Schooner Museum (ii) The Row Housing project (iii) A Branch Library. The studio statement suggests that these three projects vary in content, scale and complexity and hopes to challenge the design student to experiment with various ways of thinking. For example, the expectations of a Schooner museum within the bounds of the design task could require more visual content, relatively worked at a smaller scale (12000 sft) and less complex in relation to the preceding projects. The row housing on the other hand requires work at a more functional level, is of a moderate scale (27,000 sft), and more complex (because of the greater number of client scenarios). The library project is the last of the studio project where students are expected to integrate their learning from the first two studios. The scale dramatically changes in terms of site development (80,000 sft) and there is a larger demand to responding to the urban context. Since the students will be handling three design problems in the course of the semester, it will give an opportunity to the researcher to see whether the multiple intelligences are used consistently or vary according to specific architectural design tasks. For the purposes of this study, the three design tasks could be seen as three different categories of architectural settings where the domain, field and individual may operate at seemingly different levels. The 410 studio at SARUP usually consists of 90-100 student population distributed in five to six sections and will also provide an opportunity to study impact of instruction styles on design.

4. Instruments: Protocol analysis and Architecture Design Intelligence Assessment Scales (ADIAS)

Two kinds of instruments will be used in the study and will be administered for two different samples. The smaller sample will consist of 10 students whose design process will be recorded through a prolonged protocol analysis lasting one semester, and recording the design process every alternate day. The larger sample will consist of 50 students for which the *Architecture Design Intelligence Assessment Scale* (ADIAS) questionnaire developed by the author (D'souza 2004) will be administered after each of the three problems are completed. Both the protocol study and the ADIAS survey questionnaire are derived from the Multiple Intelligence Development Assessment Scale (MIDAS) developed by Shearer (1999) to assess Multiple Intelligence theory of Gardener. MIDAS consists of 8 intelligence scales (relating to Gardner's eight intelligences) and 24 skill subscales. The transformation of MIDAS scales to ADIAS scales will be done in three stages and by using the entire pool of 90 students so that there is sufficient evidence of reliability

Currently protocol studies are used only in experimental setups (Tang and Gero, 1999) where a small number of participants are observed in a room and who are expected to design a product in a short period of time (2 to 4 hrs.). The short duration not only diminishes the quality of architectural design, but also fails to simulate the naturalized setting of an office or school. The 410 studio projects on the other hand allow for a problem that is close to a naturalized practice environment lasting for duration of approximately one month per project. Moreover, the researcher can interact with the designer without overtly intervening in the spontaneity of the design process. Students also have a longer time to work on the project and hence may be more responsive to the investigation rather than responding to a short psychometric assessment.

5. Data collection and Coding

Since the protocol analysis attempts to capture the design process as a sequence of events in time, the researcher will observe and interact with the designer every alternate day and record the process verbally. No audio or video camera will be used because the researcher wants to avoid unnecessary interventions during the design process. To supplement the verbal information, however, the drawings will be recorded using a digital camera wherever seems fit (Table 2). The student will also be asked to keep a log book so that informal sketches and information could be recorded throughout the design process. The digital recordings will be done usually at the end of the observed period so that the student work is not compromised or hindered. Since, a large quantity of data will be generated during the design process, for data reduction purposes, data will be recorded not as an entire transcription, but as design intents. Later these intents can be matched with the particular characteristics of MIDAS main scales and analyzed.

For example the design intent 'take advantage the view towards downtown' could indicate that it has the characteristics of *spatial* (S) and *logical intelligences* (L) and recorded as shown in table 3. To further fine tune this observation, the design intent can also be placed on the particular MIDAS subscale such as *space awareness* (SA) under spatial intelligence and *everyday problem solving* (EPS) under logical intelligence. To increase reliability two or three coders could check on whether particular design intent matches with the particular characteristic of the MIDAS scale. A codebook will be provided to these coders with probe questions to guide their evaluation in relation to architecture design (see table 4). These coders will be preferably architects who are in a better position to read architectural drawings and design intentions. There could be cases, however, when design intents may not be coherent enough to be placed in any of these categories, or the MIDAS scales may not be sufficient enough to describe particular design intent. In such cases, data will be recorded separately as a miscellaneous item and will be discussed with the coders on its validity.

TABLE 2. Example of Design intent

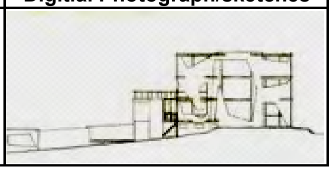
Case No	**Date**	**DI no.**	**Design Intent**	**Digitial Photograph/sketches**
		1	Take advantage of downtown view	

TABLE 3. Recording

<table>
<tr><th colspan="26">Multiple Intelligences</th><th rowspan="2">Miscellaneous</th></tr>
<tr><th colspan="26">MIDAS main scale</th></tr>
<tr><td colspan="4">M</td><td colspan="2">K</td><td colspan="4">L</td><td colspan="3">S</td><td colspan="3">V</td><td colspan="3">I</td><td colspan="4">P</td><td colspan="3">N</td><td rowspan="5"></td></tr>
<tr><td colspan="4"></td><td colspan="2"></td><td colspan="4">✓</td><td colspan="3">✓</td><td colspan="3"></td><td colspan="3"></td><td colspan="4"></td><td colspan="3"></td></tr>
<tr><th colspan="26">MIDAS sub scale</th></tr>
<tr><td>AP</td><td>IS</td><td>VA</td><td>CO</td><td>AT</td><td>DT</td><td>SM</td><td>LG</td><td>EM</td><td>EPS</td><td>SA</td><td>AD</td><td>WO</td><td>EXS</td><td>RS</td><td>WA</td><td>SP</td><td>SSE</td><td>IW</td><td>PK</td><td>CA</td><td>SPS</td><td>EFF</td><td>AC</td><td>PC</td><td>SC</td></tr>
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</table>

TABLE 4. Example of the Codebook for Logical Intelligence

LOGICAL-MATHEMATICAL	L	To think of cause and effect connections and to understand relationships among actions, objects or ideas. To calculate, quantify or consider propositions and perform complex mathematical or logical operations. It involves inductive and deductive reasoning skills as well as critical and creative problem-solving		Do the concepts, spaces, forms, details follow a logical order. Do they convey logical analysis (for example site analysis) . Do the drawings and intentions convey analysis of precedents and use them effectively in design.Understand and apply technology. Design which is research oriented/ confluence of a wide variety of fields
Everyday Math:	EM	Used math effectively in everyday life		Do the features convey mathematical abilities such as evidence of area estimation, load calculations, lighting numbers and so on. Sensitivity to issues of geometry and grid
School Math:	SM	Performs well in math at school		
Everyday Problem Solving:	EPS	Able to use logical reasoning to solve everyday problems, curiosity		Do the drawings and intentions convey patterns, sensitive to practical and common sensical issues. Understand what fits a particular problem and what does not.
Strategy/Logic Games	LG	Good at games of skill and strategy		Do the drawings convey ability to provide alterntaive solution and big ideas effectively. To bring together a wide amount of information and to make it part of a general and effective plan of action. Ability to look at macro and micro scales of information. Speed at figuring out the problem. Ability to break down a larger problem into sub-problems. Comprehension and translation.

6. Strengths and limitations

The combination of the two instruments: the protocol analysis (which attempts to record and measure interaction between the designers abilities and a specific design task) and the ADIAS questionnaire (which attempts to measure general information regarding the domain individual & field characteristics) could provide a valid way of looking at both the generic and specific use of Multiple Intelligences in architectural design. Moreover, the prolonged duration simulates the process in a natural environment such as architectural practice without reducing the study to an artificial experimental setup as done in conventional protocol analysis. The reliability of the measurement is also improved because this study is not a one time survey but a consists of continuous assessments and is based on a already validated scale MIDAS.

However, the study also has many limitations. The measurement is done in an academic setting and hence the domain and the field within which the student operates may not be similar to architectural practice, let alone similar to higher level students. Hence, transferability of the results to other academic settings or practice must include a reference to the differing nature of domain and field as expressed in the Domain-Individual-Field interaction model (DIFI model). Moreover, the research design focuses on individual acts of designing, and its validity to collaborative design may not be certain. Since, the sample is made up of only one level architecture students (sophomores), this could deter understanding the developmental aspects of multiple intelligences in architecture schools. Some scales such as musical scales could be harder to determine than other scales such as spatial scales. Moreover there could be a bias in collecting information related to intelligences that are describable (spatial, logical) as compared to those which are not (interpersonal, intrapersonal and so on). This could also pose a problem in the interpretation of protocol, especially when outside coders have limited information to work with.

Acknowledgements

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AUTHOR INDEX

Attfield, S 417
Bar-Eli, S 269
Bilda, Z 159, 315
Birkhofer, H 393
Blandford, A 417
Bonnardel, N 21
Casakin, H 93
Cavallin, H 377
Chiang, Y-C 41
Choulier, D 213
Clarkson, PJ 385
Crilly, N 385
Cross, N 307
Culley, S 195
D’Souza, N 425
Darlington, M 195
Dasgupta 109
Decortis, F 175
de Grassi, M 409
Eckert, C 3
Elias, JS 109
Gero, JS 159, 249, 349
Giretti, A 409
Goldschmidt, G 369
Gul, F 315
Heylighen, A 377
Jänsch, J 393
Jin, ST 75
Joel, S 331
Jupp, J 349
Kan, J 249
Karvinen, M 231
Kim, YS 75
Kreitler, S 93
Lawson, B 307
Leclercq, P 175
Lee, HS 75
Lindemann, U 289
Liu, F 195
Lloyd, P 59
Martin, WM 377
McMahon, S 195
Maher, ML 315
Marmèche, E 21
Mengoni, M 409
Mottram, C 417
Nevala, K 231
Parthenios, P 401
Pena, E 213
Penn, A 417
Rodgers, P 331
Saariluoma, P 231
Safin, S 175
Schiek, AFG 417
Schneider, S 289
Smyth, M 331
Stacey, M 3
Suwa, M 35
Tang, H-H 129
Van der Hoog, W 59
Van der Poel, I 59
Wakkary, R 301
Wang, M-H 41
Wild, P 195
Woodcock, A 141