A switching coding scheme for exploring design cognition in mixed media design environments

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ABSTRACT: Mixed media design environments comprise conventional and digital tools, the combination of which is often better than individual tools during the conceptual design phase (Ibrahim and Rahimian, 2010). Both pen-paper sketching and CAD (computer-aided design) modelling are the most popular tools for the contemporary design industry and the education behind it (Romer et al., 2001). When designers switch from sketching to CAD modelling, the shift action of re-thinking the early design improves design creativity (Chen, 2007). In studies into mixed media design environments the focus is often on the early design process, the designers being asked to start by sketching then move to CAD modelling: this method of using mixed media containing one shifting action is called sequential mixed media (SMM). However, there is another way of using mixed media, called alternate mixed media (AMM), in which designers alternate frequently between the two. There is an inadequate number of studies into exploring designers' behaviour in AMM, their shifting actions between tools and the factors triggering the shifting actions. This paper commences with a comprehensive analysis of a wide variety of design tools supporting conceptual design in the early design process; then presents a switching behaviour coding scheme for future study into investigating design cognition between SMM and AMM. The outcome will lead to a more critical understanding of how use of both design tools can be facilitated – more particularly, when and why designers shift from one tool to another tool during the conceptual design phase.

Conference theme: Computer Science
Keywords: Design Cognition, Mixed Media, Design Process, Switching Behaviour Coding Scheme.

INTRODUCTION

Mitchell (1993) strongly recommends a wider application of the different technologies in the design process acknowledging the potential influence between the sketching and digital modelling: an important aspect of this potential is the possibility of using CAD to develop ideas in the early design stage (Mitchell, 1993). Mixed media is believed to enhance the generation of ideas, design communication and decision-making during the conceptual design phase (Ibrahim and Rahimian, 2010). Although there is a variety of research into design tools examining the way in which designers in solo or mixed design environments utilise conventional and digital media, it is not yet clear how the different ways of utilising the tools affects design cognition, specifically during the conceptual design phase, nor what the design processes and strategies of representing the traditional and digital media at higher levels of design cognition.

Several studies explore different types of design media: using a solo design tool during the conceptual design phase (Kavakli and Gero, 2001, Aliakseyeu et al., 2006, Gu et al., 2011, Schweikardt and Gross, 2000); comparing two solo tools in design (Sachse et al., 2001, Won, 2001, Kim and Maher, 2008); comparing solo and mixed design environments (Ibrahim and Pour Rahimian, 2011), e.g. Sachse et al's (2001) study of more than 100 expert engineering designers utilising sketching before and during CAD modelling; found an improvement in the quality of solutions, reduction of time taken and also in the number of processing steps taken in CAD. However, their work did not consider the design activity from a cognitive perspective, specifically the changes of design behaviour in the mixed media environment or the difference between using sketching before and during CAD modelling.

This paper reports on a projects which aims to develop a new coding scheme extending the existing design process and strategies schemes in design cognition, the Function-Behaviour-Structure (FBS) model (Gero, 1990) – adapting it to suit the context of designing in alternate mixed media (AMM) for the purpose of understanding designers' behavioural changes in mixed media environments; and to identify the factors triggering shifts between tools. This paper provides a wide-ranging analysis of a designer's use of design tools, and the rationale for why mixed sketching and CAD modelling design environments require further study. The final section presents protocol analysis, develops a switch behaviour coding scheme and discusses the mixed media theory. The significance of this paper is its contribution to the better understanding of the changes in designers' behaviour in mixed media design environments and the triggering factors involved.

1. RELATED WORKS

Following is the consideration of the current knowledge of the different types of design media, drawing a comparison between the two solo design environments (sketching and CAD), and comparing solo and mixed design environments.

1.1. Types of design environment

The early design process is seen as the cognitive activity of organising ideas to find a solution: it involves both synthesis and analysis of various perspectives of the requirements for finding the main solution. Many designers use visual thinking aided externally; they better understand an idea by sketching it on paper to see if it works. The process by which images are used as fundamental objects for design decision-making is called 'graphical thinking' (Laseau, 1989), 'design drawing' (Lockard, 1982), or simply 'sketching': this iterative method of testing ideas and informing the design phase using images basically directs and aids the designer's decision-making; and is referred to as *'the insightful conversation with images and ideas delivered by the act of drawing'* (Schon and Wiggins, 1992). With Schon's argument we can infer that the reflective conversation is about the designer's *'seeing what is there, drawing in relation to it, seeing what is drawn'*, thus further developing the design; so one of the most important tools that designers have at their disposal in the early design stage is freehand sketching.

In spite of being a premium tool for design there are some constraints in the design activity of sketching. Sketching is a passive tool and relies on initiative from the designer. The fact that sketching isn't digital is the main constraint. All information in industry requires transferring the sketching data into digital format, this being considered a barrier for their concurrent use (Herbert, 1993).

Computer-Aided-Design (CAD) was first developed in the 1960s and has progressed to being an intricate part of architecture (McFadzeam, 1999). Kiviniemi and Penttilä (1995) consider that the major difference between CAD modelling and sketching, the traditionally accepted design medium is the lack of an unambiguous scale. As well, designers use mouse, keyboard and screen design – very different from using pencil and paper: this can initially be a great difficulty because there is no direct physical connection between hand and eye (Ekelund et al., 1992). Sketch design work is done on a sheet at one time, but CAD modelling builds the 3D model through 2D layout, perspective, and other detailed section views (Haapasalo, 1997). The results of design are usually several drawings or one 3D model of the building that is always done in real scale (Penz, 1992). The earliest conceptual design phase for starting with CAD working and the following design phase such as detail design is only need a fine-tuning. The types of design media such as sketching, CAD modelling, and other types of digital tools during the early design process are detailed in Table 1.

Table 1: Types of design environments

Type 1: Sketching (pen and paper)	
Scholars & year	**Research findings**
(Ullman et al., 1990)	The beginning of the action of the sketch is *'to archive the geometric form of the design'*. Sketches provide a way to store the conceptual ideas, so designers can revisit drawings from different point of views.
(Fish and Scrivener, 1990)	Sketching mediate mental translation between spatial cognition and structurally descriptive modes of the visual demonstration.
(Goldschmidt, 1994)	'Seeing-as' and 'seeing-that' modes were developed by observing that architectural students generate unclear and ambiguous sketching that is a significant element of design creativity during the design stages. A designer frequently uses sketches as descriptions of the objects to be designed – called 'interactive imagery'.
(Schon and Wiggins, 1992)	Designing as a conversation with materials via sketching, importantly dependent upon *seeing*. The different types of designers' movements are described as 'seeing–moving–seeing'.
(Scrivener and Clark, 1994)	Sketching provides representations of design solutions that allow for a variety of interpretations and sequential decisions are made that allow for evaluation and interpretation of the design solutions.
(Suwa and Tversky, 1997)	The reinterpretation of the new ways of seeing or shifting focus can contribute to the creative process.
(Purcell and Gero, 1998)	Focus on the role of sketching in design cognition and description of such reinterpretation as *'new ways of seeing of a potential design'*.
(Kavakli et al., 1998)	Drawing behaviour is affected both by task and stage. The sketching behaviour might provide important insights into the nature of the idea development process.
(Verstijnen et al., 1998)	'Combining, Restructuring, Expertise, and Creativity' will separately impact on sketching behaviour. On the basis of their results conclusions are drawn for computerised sketching aids.
(Scrivener et al., 2000)	'Top-down cognitive factors, perception, or a combination of both could trigger switching of drawing behaviour. From the evidence, it is concluded that uncertainty is the primary factor triggering change in drawing structure.'
(Rodgers et al., 2000)	Freehand sketching is prevalent in the conceptual phase of design and the sketching activity has peaks and troughs of both 'lateral and vertical transformations' over time. In this way, sketching can provide insight into the designer's thinking at any particular point in the

	design process.
(Kavakli and Gero, 2001)	Results show that there are differences in the balance of cognitive actions between novice and expert designers.
(van der Lugt, 2005)	The results show that relevant functions of sketching are: firstly, supporting a re-interpretive cycle in the individual thinking process; secondly, enhancing access to earlier ideas.
(Goldschmidt and Tatsa, 2005)	Intensive interlinking among design ideas, design decisions or design moves is the hallmark of good and creative design. Therefore, the answer to the question 'how good are good ideas?' is simply: ideas are as good as suggested by the network of links they create among themselves.
(Menezes and Lawson, 2006)	Evidence from both cognitive psychology and design research supports that the designers, particularly during the conceptual phases of the design process, have a strong interaction with their own sketching. This interaction with sketching seems to be related more to designers than to the action of drawing. The way designers describe things might reflect the way they think, and new thoughts might emerge when they interact with sketching.
Type 2: Digital sketching (Sketch tablet & TUIs)	
Scholars & year	**Research findings**
(Verstijnen et al., 1998)	Electronic sketch tablets, like paper and pencil, support unspecified input idea creation tools. Currently these tablets lack support facilities for restructuring. The efficiency of these tablets for the purpose of idea sketching could be considerably improved.
(Aliakseyeu et al., 2006)	Instead of trying to replace such conventional ways of working, there is attempt to maintain the strengths of these conventional ways of working while at the same time improving them by providing access to new media. The realisation of a tool for early architectural design on an existing augmented reality (AR) system, called the 'Visual Interaction Platform'.
Type 3: 3D virtual worlds and TUIs	
Scholars & year	**Research findings**
(Gu et al., 2011)	The problem is that many design projects occur at the same time but in different locations. They conduct two protocol experiments in 3D virtual worlds: remote design collaboration and collaboration with tangible user interfaces (TUIs), the former to understand the behaviours changing when physically remote but virtually co-located in 3D models. Later study improves designers' cognition when using TUIs combined with augmented reality (AR).
Type 4: Digital clay	
Scholars & year	**Research findings**
(Schweikardt and Gross, 2000)	Digital Clay, a working prototype of a sketch recognition program that interprets gestural and abstracted projection sketching and constructs appropriate 3D digital models.
Type 5: CAD modelling	
Scholars & year	**Research findings**
(van Dijk, 1995)	CAD can fulfil the same role for sketching as word processors do for writing. However, at the moment CAD is still in the 'typewriter' era. If CAD can speed up in terms of UI or hand movements, traditional drawbacks would be eliminated.

1.2. Means for comparing two solo design environments

Table 2 shows that designers using sketching have the better synthesis strategy than using CAD modelling (Bilda and Demirkan, 2003, Stones and Cassidy, 2007). Digital sketching and conventional sketching have no significant differences, because of the features of these two different design tools (Won, 2001). Thus, both sketching and CAD modelling can be used in the early design processes.

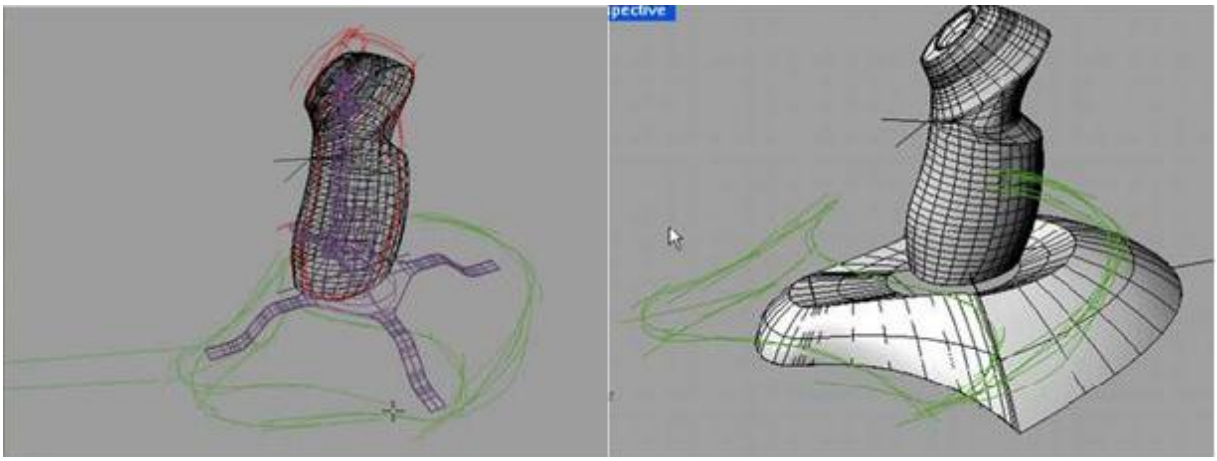
Table 2: Comparing two solo design environments

Type 1: Sketching vs CAD modelling	
Scholars & year	**Research findings**
(Won, 2001)	When designers use conventional media to generate concepts, their cognitive behaviours are simpler than when they use computer tools. The representation of preliminary sketching, the stroke representing the traditional way, is rough, while the CAD way is concrete.
(Bilda and Demirkan, 2003)	Traditional media have advantages over digital media, such as supporting the perception of visual spatial features and relationship of the design, production of alternative solutions and better conception of the design problem.
(Stones and Cassidy, 2007)	Not only is paper-based sketching more effective in producing more solutions than digital work, but also more effective in supporting one particular synthesis strategy.
Type 2: Conventional sketching vs Digital sketching	
Scholars & year	**Research findings**
(Tang et al., 2011)	The design processes using traditional and digital sketching are not yet statistically different.
Type 3: TUIs vs GUIs	
Scholars & year	**Research findings**
(Kim and Maher, 2008)	The main problem of GUIs is that designers cannot design intuitively because they have to use a keyboard and mouse. The results reveal that when designers using TUIs, the inter-

	face changes their spatial cognition and improves problem-finding behaviour.

1.3. Ways of comparing solo and mixed design environments

Table 3 shows comparisons of mixed media to solo media. Interestingly, Huang and Lee's (2004) conduct a comparison experiment – conventional sketching and CAD modelling vs digital sketching and CAD modelling – in which they found that with digital sketching and CAD modelling the designer remained aware of cognitive sketching behaviour while building CAD modelling (Figure 1a). However, digital sketching cannot show all the drawing processes on-screen, and when moving or rotating the 3D model the drawing cannot be matched (Figure 1b).



Source: (Huang and Lee, 2004)

Figure 1a: digital sketching while CAD modelling; Figure 1b: sketching and CAD modelling have a mapping problem

Table 3: Comparing solo and mixed design environments

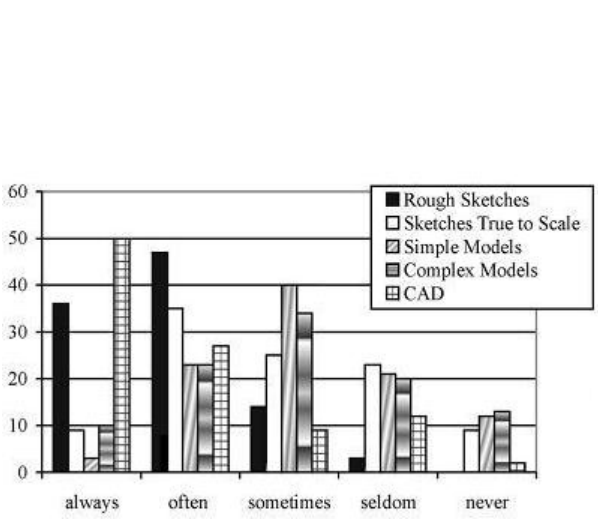
Type 1: Full sketching vs Mixed media vs Full CAD modelling	
Scholars & year	**Research findings**
(Ibrahim and Pour Rahimian, 2011)	Using mixed media is superior to fully sketching or fully CAD modelling. A VR-based alternative design interface would improve design representation and, hence, enhance cognition and communication among novice designers during the conceptual design phase.
Type 2: Conventional sketching and CAD modelling vs Digital sketching and CAD modelling	
Scholars & year	**Research findings**
(Huang and Lee, 2004)	A new formula for employing digital media that will enable the designer to imagine 2D sketches and computer models simultaneously. In this scenario, the designer can remain aware of cognitive behaviour in sketching while constructing computer models.
Type 3: Haptic CAD & digital sketch vs Physical model & traditional sketch	
Scholars & year	**Research findings**
(Rahimian and Ibrahim, 2011)	Traditional tools (freehand sketch, mock-up) and a haptic device with tangible interface digital tools are compared to understand novice designers' spatial cognition. Main findings show significant improvement for designers' spatial cognition with the haptic device. However, it's expensive, and many designers have no experience of such media.
Type 4: Full sketching vs Mixed media vs Full CAD modelling	
Scholars & year	**Research findings**
(Chen, 2007)	Studies graphic design by using conventional and digital media simultaneously and finds that design creativity occurs when shifting tools.

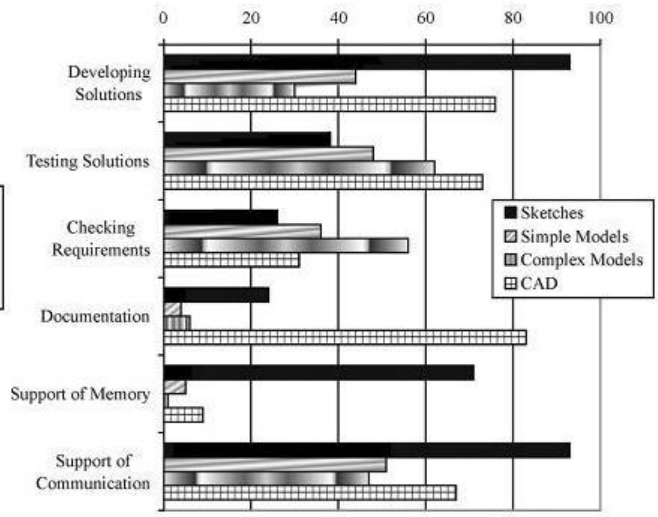
1.4. Why study mixed sketching and CAD modelling design environments?

Romer et al. (2001) through the use of a survey of 106 designers enquired 'how often do you use …?' and 'what do you use … for?' in terms of sketches, models and CAD. Figure 2a shows that rough sketching is the most popular external tool; but there is no significant difference between rough sketching and CAD overall. Figure 2b shows that sketches are used significantly for solution development, supporting the memory and communication; while CAD is used largely for solution development, testing solutions, documentation and supporting communication. These are the most popular and functional external tools, and the main focus of this research project.

Many architects still prefer to use pen and paper or scale models in the early design stage (Gross and Do, 1996), though in the Gross and Do report that it offers the required flexibility, speed and intuitive interaction. This way of working, however, creates an interruption in the design process flow; since the designers have to transfer their design works to CAD modelling specifications after the early design stage. In order to reduce the time spent on this transition, more and more architects are using programs like AutoCAD and ArchiCAD in all stages (Lawson, 1999). In interior design, the ideation process is based on the technical plan of the space, followed by freehand perspective views or accurate perspective rendering (Dorta and Perez, 2006). On one hand, the problems of freehand sketching appear to be understanding complex 3D shapes, unconscious proportion errors, disregard for human scale, and the

observer's angle of vision (Landsdown, 1994); while on the other hand, typical computer representation can affect the conceptual design process – the interface, the accuracy, the lack of abstraction and absence of ambiguity. Most of the solutions proposed to integrate the sketch into the digital design process seem to take a particular path to imitating or simulating the real sketch (Jatupoj, 2005).





Source: (Romer et al., 2001)

Figure 2a: Frequency of use of external representations (in %); Figure 2b: Purposes of using external representations (in %)

2. COGNITION IN MIXED MEDIA DESIGN ENVIRONMENT: AN APPROACH

Table 4 provides an overview of research methods previously used on designers' behaviour whilst utilising external aids such as sketching or CAD. Protocol analysis has been employed in an endeavour to better understand the difference between novice and expert designers (Kavakli and Gero, 2001), the study of design strategies (Stones and Cassidy, 2007), and the comparison of traditional and digital sketching (Tang et al., 2011). Researchers have combined two methods, protocol analysis and the analysis of variance (ANOVA), to understand the design process as well as evaluate design outcomes (Sachse et al., 2001, Ibrahim and Pour Rahimain, 2011); these would all support the application of Protocol Analysis as an appropriate method for better understanding the design activity in a mixed media situation.

Table 4: Types of research methods

Method 1: Protocol analysis	
Scholars & year	**Procedures**
(Kavakli and Gero, 2001)	**Subjects:** novice and expert designers **Coding scheme:** adapted from Suwa and Tversky (1997) **Design media:** sketching
(Stones and Cassidy, 2007)	**Subjects:** student designers **Coding scheme:** develop six types of synthesis strategies: unconnected, touching, overlapping, enclosed, joined, and contributing **Design media:** digital and paper-based tools
(Tang et al., 2011)	**Subjects:** novice designers **Coding scheme:** adapted from Gero's FBS model **Design media:** traditional and digital sketching
Method 2: Combined protocol analysis with ANOVA	
Scholars & year	**Procedures**
(Sachse et al., 2001)	**Subjects:** novice designers **Evaluation criteria:** six types of physical operation steps **Design media:** CAD modelling and CAD modelling with sketching
(Ibrahim and Pour Rahimian, 2011)	**Subjects:** novice designers **Coding scheme:** adapted from M.Schtze et al. (2003) **Evaluation criteria:** score 1 to 5 for assessing the quality of the solution **Design media:** sketching, CAD modelling, and mixed media
Method 3: Combined protocol analysis with Linkograph	
Scholars & year	**Procedures**
(Goldschmidt, 1990)	Every pair of moves in a given sequence of moves is checked for the existence of links, which are then notated in a graph called Linkograph.
Method 4: Combined questionnaire survey with SPSS	
Scholars & year	**Procedures**
(Römer et al., 2001)	200 questionnaires posted to designers, 106 completed questionnaires sent back. Questionnaire data analysed by employing descriptive statistics.

2.1. Protocol analysis

Protocol analysis has been accepted as a prevailing approach for elucidating the design process in the design community; it is an experimental technique to clarify understanding of how designers think. This is a methodology which often uses the *"think aloud"* approach to documenting and analysing a designer's decision-making processes; it is an ethnographic approach to capturing and analysing thought processes as they inform the physical actions of the designer.

Many scholars separate the protocol technique into two categories – retrospective and concurrent protocols. Concurrent protocols focus on a process-oriented aspect of designing based on the information-processing view; while retrospective protocols focus on a content-oriented aspect of designing based on the reflection-in-action view (Schon, 1983). Much protocol research has asked subjects to think aloud and sketch simultaneously. Ericsson and Simon (1993) initially study protocol analysis as a valid technique for using utterances to explore the human cognitive activities. Retrospective protocols utilise the retrospective report method: a participant is asked to report their thinking after the task. Therefore, the protocol method is suitable for all designers in the experiment.

To achieve the aims and objectives we adopt the following two types of protocol analysis: think-aloud and retrospective methods. The think-aloud method asks participants to verbalise while they carry out problem-solving activities (Ericsson and Simon, 1993); it can retrieve sequential information and design strategies during designing, based on short-term memory. The AMM design environment could make it difficult to explore the reasons for participants' switching between the two design tools in the early, middle and later design processes of the conceptual design phase: retrospective protocol is an appropriate methodology to investigate the notion of reflection-in-action (Schon, 1983) and perceptual aspects such as triggering factors relating to designers. The method has been conducted with video aids to enhance retrieval from long-term memory (Suwa and Tversky, 1997). The two kinds of protocols will assist in better understanding the impact of AMM.

2.2. Gero and Suwa's coding scheme

Designing is a purposeful action that includes thinking, evaluation and decision making. External tools such as sketching and CAD modelling have the potential to enhance complex problem analysis, solution generation, evaluation and external storage (Romer et al., 2001, Sachse et al., 1999). Gero (1990) devises a design prototype model called Function-Behaviour-Structure (FBS) to retrieve design processes and information. The FBS model has the categories- requirements, function, expected behaviour, structural behaviour, structure, and description. Table 5 defines these:

Table 5: Categories of Gero's FBS coding scheme

Categories	Description	Examples
Requirements (R)	The final goal of designing is to transform a set of requirements (R).	Yes, I'm an eight.
Function(F)	The function (F) of an object is defined as its intended purpose or teleology.	I do lots of walking, so
Expected Behaviour (Be)	The behaviour of the design is expected (Be).	But, you know, if you have something that goes with every thing you wear.
Structural Behaviour (Bs)	The behaviour of the design is derived from its structure (Bs).	I like ... the style of the shoe.
Structure (S)	The structure (S) describes the components and their relations in the design.	Do I select all those material? Or...
Description (D)	Functions into a set of descriptions (D).	[Description] selecting size.

Source: (Gero et al., 2011)

The main purpose of coding schemes, especially when analysing AMM, is to classify protocol data retrieved from the three design environments. Our hypotheses are that

- AMM involves many switching actions which may change the design process, and that
- these changes affect design strategies which facilitate problem-solving.

With regard to the design process and strategies, the FBS coding scheme will be adopted (Gero, 1990), with its six categories and associated eight design strategies of formulation, synthesis, analysis, evaluation, documentation, reformulation 1, 2, and 3 (Table 6).

Table 6: Categories of FBS design strategies

Design strategies	Description
Formulation	Formulation which transforms functions into a set of expected behaviours (F>Be).
Synthesis	Synthesis, where a structure is proposed to fulfil the expected behaviours (Be>S).
Analysis	An analysis of the structure produces derived behaviour (S>Bs).
Evaluation	An evaluation process acts between the expected behaviour and the behaviour derived from structure (Be>Bs or Bs>Be).
Documentation	Documentation, which produces the design or partial design description (S>D).
Reformulation 1	Reformulation of structure (S>S).

Reformulation 2	Reformulation of expected behaviour (S>Be).
Reformulation 3	Reformulation of function (S>F).

Source: (Gero et al., 2011)

For the switching behaviour aspect, participants will be asked to look in retrospect on each shifting behaviour, so we will be adopting Suwa et al.'s (1998) four-level coding scheme of physical, perceptual, functional and conceptual (Table 7). These two types of coding scheme have been widely used for exploration into design cognition research.

Table 7: Categories of Suwa's coding scheme

Four Categories	Description
Physical	Refers to actions that have direct relevance to physical depictions.
Perceptual	Refers to actions of attending to visuospatial features.
Functional	Refers to actions of conceiving of non-visual information which depicted elements and their visuospatial features are able to carry.
Conceptual	Refers to cognitive actions that are not directly suggested by physical depictions or visuospatial features of elements.

Source: (Suwa et al., 1998)

CONCLUSION AND FUTURE WORK

Thus far the paper has provided a rationale and a methodology for the need to better understand the design activity and the cognition which underpins it in an AMM design environment. The next phase of the project is to conduct a pilot study for the purpose of gathering information regarding design cognition for analysis of designers' behaviour while they are working on mixed media design environments (SMM and AMM). The Pilot Study has two functions: (1). to explore whether the experimental design is achieves the purposes of the project and satisfying the research requirements; (2). to test whether meaningful patterns emerge through the application of the adopted the coding schemes. The pilot will involve two architectural design students who are competent with both sketching and CAD modelling. Two design tasks with similar complexities are a two-floor design office and a two-floor dream apartment, and they will be used randomly for the participants. There are five steps to analyse protocols of the pilot study: (1). Transcribing the protocols. (2). Segmenting the protocols. (3). Coding the protocols. (4). Generating linkographs. (5). Interpreting the results of these measures. This paper identifies a gap in our understanding of the impact of mixed media design environments that integrate digital technologies – i.e., CAD modelling – with traditional modes of design such as sketching. The paper precedes the research instigation, but provides an appreciation of need and an approach to gain a better understanding of the application of tradition and current technology in support of the design process.

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