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Behavioural Design Protocols in Architectural Design Studios: A Microscopic Analysis

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ABSTRACT

Due to the emerging complicated global design problems, new design research methodologies need to analyse the structures and processes of design cognition for discovering multi-aspect and multi-variable design strategies. Adapting such objective methods of design assessment, as opposed to the traditional survey based subjective methods of design performance studies, is therefore essential for improvements of design education in rapidly developing Malaysian design schools. This paper proposes *Protocol Analysis Methodology* for facilitating microscopic study of educational design performance assessment. Protocol Analysis has become the most prevailing research methodology for design research over the last two decades; and can be considered as a reliable methodology due to its objectiveness and accuracy in studying designers' cognitive actions. This paper illustrates how the protocol analysis methodology was used in one experiment for comparing designers' creativity when working with two types of design media, namely, traditional sketching and Virtual Reality 3Dimentional sketching. In this study, a descriptive statistical analysis on protocol data conveyed insight into novice designers' cognitive protocols microscopically in form of various charts and graphs. Results offered objective insights into the changes in the design process that were associated with applying different design media. This paper presents background literature, explains the conducted protocol analysis experiment, and presents results from the protocol data to reveal designers' action and thought protocols. This paper also recommends the application of protocol analysis methodology for performing microscopic design study in architectural education in Malaysia. The methodology could also be extended to cover other fields of design in the country. This study recommends the use of protocol analysis methodology to provide empirical data from codification of subjective observations, hence, becoming

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a stepping stone for leveraging research on teaching and learning in architectural design studios in Malaysian universities.

Keywords: Design studies, protocol analysis, design process, microscopic assessment

INTRODUCTION

Designing is one of the most important activities that distinguishes humans from other beings (Cross, 1999). The emerging globalisation and sustainability issues, combined with the advanced design support technologies, urge building professionals to explore more alternatives for more objectives. Since such 'multi-aspect' design problems are often far too much complicated for the human cognition to involve trade-offs among different variables, the ability to assess the 'new' design strategies has become progressively more essential (Clevenger & Haymaker, 2011). Although various design performance assessment methods do exist, there is an increasing interest in using advanced methodologies which analyse the structures and processes of design cognition in order to describe designers' behaviours and performance (Dong *et al*., 2012). Notwithstanding the advantages, such methodologies are often neglected in the assessment of design studio performance in architectural schools which is still using the traditional subjective questionnaire based assessment methods.

Due to the subjective or tacit nature of design process, it is often difficult to assess it using self-report survey methodologies (Bilda & Demirkan, 2003; Kim & Maher, 2008). In other words, designers are often unable to explain their cognitive thinking processes as they are not actually aware of the quality of these procedures (Clayton *et al*., 1998). Another alternative way of assessing design process is evaluating the design artefacts (Demirkan & Afacan, 2011; Ibrahim & Pour Rahimian, 2010). Although this method can reveal some invaluable facts regarding the quality of work undertaken during the design process (Sarkar & Chakrabarti, 2011), it still ignores a lot of cognitive procedures through which 'creative' design ideas can emerge (Rahimian & Ibrahim, 2011). Thus, mapping such cognitive procedures may open up a lot of opportunities for future developments. Thereby, there is an interest in design education to have some kinds of predictive tests based upon the design process and developing objective and accurate design assessment tools (Kan, 2008). Due to this tendency towards the objective ways of studying designers' problem-finding and problem-solving processes, protocol analysis is becoming the worldwide prevailing method in design studies.

This paper proposes the use of the design protocol analysis methodology in order to replace the existing subjective design assessment methods that are currently used in Malaysian architectural schools. The paper presents a background literature review regarding cognitive approaches to design and design protocol analysis methodology. It also explains the different types and approaches in design protocol studies. In addition, this paper also presents the conducted sample protocol analysis study during an experiment for comparing designers' creativity when working with two different types of design media, namely, the traditional pen and paper sketching and Virtual Reality Three-Dimensional sketching. It also explains how this conducted study generated graphical results from protocol data in order to microscopically analyse the three pairs of designers' actions and thought protocols. It finally advocates further development of such cognitive based quantitative design research methodologies as a new paradigm in Malaysian architectural design studies.

LITERATURE REVIEW

Cognitive Approach to Designing

Kan (2008) defined design as a series of decisions which expose the relationship of geometries, materials and performance. In this definition, the central activities of designing are independent of different design disciplines and scientifically observable. Seminal literature regarding design studies clustered design activities as thinking and knowing (Cross, 2007), free-hand sketching and interactions (Lawson, 1997), social construction of design solutions (Pour Rahimian *et al.*, 2008), and designing-by-making (Jones, 1970). Kan (2008) further asserted that some of design activities are more difficult to observe (and predict) as compared to the others.

Visser (2004) critically reviewed the seminal theories regarding cognitive approach to designing. According to Visser (2004), the majority of published literature in the field followed the principle of either *"symbolic information-processing (SIP)"* approach (Simon, 1979) or the *"situativity* (SIT)*"* approach (Schön, 1983). The focus of SIP approach is on designers and the cognitive processes through which they synthesise design problems and undertake rational problem-solving processes to propose solutions. However, the SIT approach relies on the designers' situational environment and context. The original SIT theory was further developed based on the constructionist view of human perception and thought processes in order to explain *"situative"* designing as a matter of *"knowing-in-action"* (Schön & Wiggins, 1992) and *"reflection-in-action"* (Schön, 1992).

From a more advanced cognitive perspective, Visser (2004) focused on the dynamic aspects of designing by analysing designers' activities undertaken in actual professional design projects. As a result of this investigation, Visser (2004) criticised both the SIT and SIP approaches and proposed a new comprehensive cognitive model through the integration of SIT and SIP approaches. Visser's (2004) comprehensive cognitive model explained designing as an *"opportunistically organised"* activity to define an artefact and evolve the characteristics which can satisfy that artefact. According to this model, design process is developed only through the evolution of internal and external representations and there is no permanent hierarchy among representations of differing levels of idea abstraction. The model also explains that ill-defined design problems can cause some interruptions which not only do not hinder design quality but also create great opportunities for improvement of design practice through reflections in actions. The model explains the value of these reflections due to the potential mutual discovery processed between the external representation and the designer's cognitive reasoning processes.

Tversky (2005) further extended Visser's (2004) model by taking a cognitive evolutionary approach. Tversky (2005) ascertained that constructing the external or internal representations, designers would be engaged with some spatial cognitive processes in which the representations serve as cognitive aids to memory and information processing. Tversky's (2005) model also combined Schön's (1983) *"Reflective Practitioner"* theory with *"symbolic information-processing (SIP)"* approach (Simon, 1979) when it defines designing as a reflective communication between the materials that belong to design situation and the internal syntheses of symbolic information that happen in designers' mind. Relying on these theories, Kim and Maher (2008) emphasised on constructive aspects of designing and explained continuous evolution of *"problem-space"* through the iterative process of *"problem-finding"* as a very important part of design process that finally leads to the maturity of *"solution-space"*, or final design artefact.

Design Ideas and Creativity

Kan (2008) argued that creative design ideas are necessary for having good design artefacts. Studying design evolution of ideas is important for design researchers as it could offer an insight into the overall strategies taken during design decision making process (Stones & Cassidy, 2007). Kan (2008) relied on Berlyne's (1971) theory regarding design reasoning and proposed that creative design ideas could only emerge through an iterative and continuous evolution process. Kan (2008) posited that too many pre-defined links among design variables could lead to early fixation of solutions which would result in too similar or boring design artefacts.

Traditionally, the term "creative" was often used as a value to evaluate a design artefact (Kim & Maher, 2008). However, in cognitive psychology, this is considered as a quality for design activity that has the potential to produce creative artefacts through particular reasoning procedures (Visser, 2004). Cross and Dorst (1999) define creative design procedures as a sort of non-routine design activities which are capable to result in considerable events or unanticipated novel artefacts. Design process is therefore meant to be evaluated based on the level of its creativeness (Kan, 2008). However, creativity is multi-aspect subject which is often defined by different mental processes which totally lead to the phase of creative insight and discovery (Finke *et al.*, 1992). According to Finke *et al.* (1992), creativity comprises of various initiative stages through which mental representations of *"pre-inventive structures"* are formed, and that this stage is prior to an exploratory stage through which the creative ideas are generated.

Meanwhile, Cross and Dorst (1999) developed cognitive approaches to design creativity and posited that it is often formed through *"co-evolution"* of *"problem"* and *"solution"* spaces. In "*co-evolutionary"* design approach (Cross & Dorst, 1999), the design brief and design solutions are formed separately, while mutually affecting each other. In a co-evolutionary approach, iterative alterations in design requirements which are determined by evolution process of design artefact could significantly affect designer's insight into design problem and this would ultimately change design solution iteratively, until both design problem and design solution reach to a *"saturation point"*.

"*Situative-inventions"* (Suwa *et al*., 2000) is a more advanced cognitive model for measuring design creativity. This model explains how designers could explore new significant parts of the design *"solutions"* when they introduce new requirements for design artefact by *"situatively"* developing design *"problem"* and going beyond the synthesis of solutions which only suit the given initial requirements. In this model, *"unexpected-discoveries"*, however, are the keys for triggering situative-inventions and making design process creative (Suwa *et al*., 2000). Suwa *et al.* (2000) defined unexpected-discoveries as the cognitive activities which articulate tacit design semantic in an unanticipated way with aid of ill-defined visuospatial forms or external representations of the ideas formed in mind. Suwa *et al.* (2000) further ascertained that the formation of unexpected discoveries of visuospatial forms and situative-inventions of new design requirements are strongly related to each other. Suwa and Tversky (2001) took a constructive approach and posited *"co-evolution"* of new conceptual semantics and *"perceptual discoveries"* could also improve designers' understandings of external representations. This was aligned with Gero and Damski's (1997) earlier finding that constructive perceptions allow designers to change their focus and to understand design problem in a different way in which re-interpretation may be stimulated, so that designers could find the opportunity to be more creative.

Based on the above discussion, it could be concluded that design creativity is a subjective matter and it could not be realised by the designers who are not aware of all these intuitive procedures that take place in their minds. Therefore, this paper argues that the existing subjective methods that are often used in architectural schools of Malaysia may not be so effective for evaluating the performance of design curricula adapted. This is because the designers are not able to explain or self-report something that they exactly do not know about. In order to fill this gap, this paper proposes the use of cognitive methods in design studies which are capable to objectively discover the tacit parts of the design process. As suggested by Clayton *et al*. (1998), adapting such research methodologies could also be useful for validating new design methodologies implemented in progressively developing architectural design schools in Malaysia. Next section provides a background literature review supporting design protocol analysis methodology (Cross *et al*., 1996; Kan, 2008) for studying design process using cognitive constructs and measures.

PROTOCOL ANALYSIS RESEARCH METHODOLOGY

Due to a tendency towards the objective ways of studying designers' problem-solving processes, protocol analysis is becoming the emerging prevailing method for design studies (Kan, 2008). Kim and Maher (2008) advocated using this methodology for analysing and measuring designers' cognitive actions instead of using subjective self-reports such as questionnaires and comments. Cross *et al.* (1996, p. 1) advocated the use of protocol analysis methodology when they mentioned:

> *"Of all the empirical, observational research methods for the analysis of design activity, protocol analysis is one that has received the most use and attention in recent years. It has become regarded as the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers."*

Protocol analysis is a method for studying design thinking and it stands between hard sciences and social sciences (Cross, 2007). According to Kan (2008), usually protocol analysis is used for identifying design activities, revealing cognitive models and knowledge structures of designer, and investigation of the perceptual aspects of sketching and designing. As a quantitative methodology, it is a new approach in design research. Akin (1998) acknowledged the design studies conducted by Eastman (1970) as the first formal protocol analysis study. In the mentioned study, using an information process model, Eastman (1970) studied what architects do when they design. This was the first model which defined design as a process of problem finding and alternative testing, rather than synthesis of structured solutions for the pre-defined problems (Akin, 1998). Later, Schön and Wiggins (1992) challenged Eastman's (1970) model when they described designing as a reflective conversation with material in which the basic structure is an interaction between designers and discovering. Nowadays, Schön and Wiggins' (1992) model is the basis of many protocol analysis studies (Kan, 2008). Relying on Schön and Wiggins' (1992) model current design protocol studies employ action analyses methods, e.g. depictions, hands movements, and looking actions, which provide a broad insight to the cognition of the physical actions involved during designing (Cross *et al*., 1996).

Strategy for Studying Protocol Data

According to van Someren *et al.* (1994), every formal design protocol analysis study should comprise of five main steps: *1) to conduct experiments, 2) to transcribe* *protocols, 3) to parse process into the segments, 4) to encode the segments based on a valid coding scheme,* and *5) to analyse and interpret the encoded protocols.* However, based on the nature of the projects, there are some paradigms which can determine the detailed strategy that researchers should follow during their protocol analysis study.

In terms of the reporting method, recent protocol analysis studies could be classified into two main categories: 1) concurrent methods, and 2) retrospective methods. Verbal protocol methodology (Ericsson & Simon, 1993) was one of the first attempts which led to the invention of the concurrent protocol analysis (Cross *et al*., 1996). Ericsson and Simon (1993) relied on the use of verbal protocols as the quantitative data for studying thought process. In a latter study, van Someren *et al.* (1994) provided theoretical framework and practical guideline to study and model the designers' cognitive processes. As depicted in Fig.1, they assumed a simple human cognitive model to develop the validity of verbal reports. The arrows in the diagram represents different processes: perception (sensory to working memory), retrieval (long-term memory to working memory), construction (within working memory), storage (working memory to long-term memory), and verbalisation (working memory to protocols).

After a few years, concurrent method was abandoned by many of the scholars because of its disadvantages (Kan, 2008). Kan (2008) described the disadvantages of concurrent reporting systems as: 1) slowing down the thinking process, 2) failing in reporting the whole thinking process when the participant stops verbalising or uses imagery only, 3) weakening the reasoning process for those participants who are not able to verbalise and reason at the same time, and 4) including some subjective elements in the coding system. As mentioned above, the alternative for the concurrent method was the retrospective reporting method with visual aids. Contrary to the concurrent method, in retrospective protocol analysis, designers are asked to remember their thoughts by using some visual aids, after they finish the design process. For this purpose, the whole process should be videotaped and thoroughly transcribed (Dorst & Dijkhuis, 1995; Foreman & Gillett, 1997; Schön, 1983).

The other classification of protocol studies is based on what the protocol study focuses on. In order to reflect the two

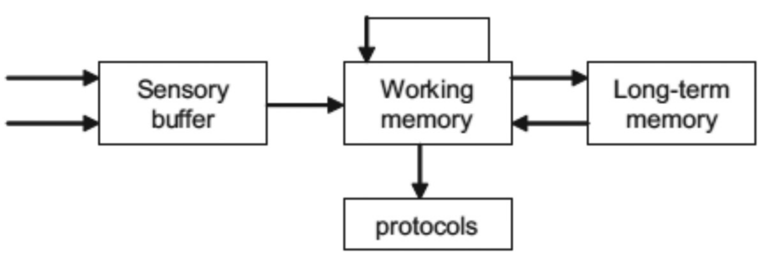

Fig.1: van Someren's memory model (van Someren *et al*., 1994)

different paradigms in design cognitive sciences, i.e., the information processing model (Eastman, 1970) and the reflection in action model (Schön & Wiggins, 1992), there are two types of protocol studies, namely, process-oriented and content-oriented protocol analysis (Dorst & Dijkhuis, 1995). The think-aloud or the concurrent protocol is usually used for process-oriented analysis in which the focus is on the process of information. Meanwhile, retrospective protocol is used for content-oriented analysis in which the cognitive content of designing is the focus. Since the conducted sample protocol analysis in this study focused on designers' cognitive activities, the content-oriented protocol analysis was selected as the data collection strategy for this research. Besides, the retrospective method of reporting was adapted since the use of concurrent methods is not suitable for collaborative works (Kan, 2008). During the sample conducted protocol study, the designers worked naturally while the entire process was recorded. After finishing the experiments, the designers were required to transcribe their sessions using the aid of the recorded media. Their transcriptions as well as the recorded media provided the research data for the subsequent coding process.

Unit of Analysis

The unit of analysis in design protocol analysis depends on the objectives and scope of studies (Kan, 2008). Kan (2008) explained that the unit of analysis could be individual participants (when studying design team working), sessions, episodes, code categories, or even each segment or utterance. In the protocol analysis studies, segments are the smallest parts of design process which could not be divided into smaller subdivisions. Example of a segment is the act of designer while drawing a circle or looking at a part of a drawing. Moreover, a segment could be a mental thinking process as considering whether a design element suits into design requirements or not. Since this study focused on designers' cognitive and collaborative actions and the tested hypotheses relied on these actions, the study chose each design segment as one unit of analysis.

Strategy in Parsing Segments

Suwa *et al.* (1998) defined the process of parsing segments as dividing the entire design process into the smallest units. However, a segment should not necessarily comprise of a single code and it might contain several codes (Suwa *et al.*, 1998). Based on the objectives and the scope of the study, researchers usually use two strategies in parsing the segments of the design process (Kan, 2008). The first strategy is segmenting the process depending on the occurrences of the processes. In this method, the purpose is to analyse the protocols in the frequencies of processes involved. Ericsson and Simon (1993) suggested some cues for segmentation, in which the cues are *pauses in the process or conversation, changing in intonation, and the contours which correspond to the designers' information processing model*. From a different perspective, Dorst and Dijkhuis (1995) suggested using a fixed 15-second time-scale for segmentation. According to Kan (2008), the ease of processing data is the advantage of this method since it does not require any interpretation during the segmentation. However, Kan (2008) asserted that since this 15-second interval segmentation method might cut in the middle of a statement, it makes the coding procedures more difficult compared to those in the previous method. As such, this study selected the first method of segmentation which depends on sequence of the occurrences of the processes.

Coding Scheme

In design studies with protocol analysis, coding schemes are meant for defining different action categories which are needed for segmentation of the process and further analysis of data. There is a variety of developed coding schemes for design protocols. The types of coding schemes, which should be used in different studies, are dependent upon the purpose and the scope of that particular study. Gero and McNeill (1998) developed a comprehensive and multi-dimensional process-oriented coding scheme which considers design as a process. The first dimension of this coding scheme was concerned with the designers' navigation within the problem domain at different abstraction levels. The second dimension looked at the designer's design strategies. The third dimension was related to the designer's cognitions about function, human behaviour, and structure. This coding scheme, however, has no dimension that focuses on collaborative activities of the designers.

Of the most comprehensive and most referred content-oriented coding schemes is Suwa *et al.*'s (1998) coding scheme (for instance used in Bilda & Demirkan, 2003; Bilda *et al*., 2006; Kim & Maher, 2008). They established their coding scheme based on the human cognitive process. Suwa *et al.* (1998) considered the content of the process semantically and categorised design actions into four categories: *1) physical actions, 2) perceptual actions, 3) functional actions,* and *4) conceptual actions*.

In Suwa *et al.*'s (1998) coding scheme, the physical action category corresponded to designers' sensory level. This category includes the categories of making depictions, examining previous depictions, and other physical actions. Perceptual action category comprised of designers' perceptions of the previous physical actions. Therefore, the coding scheme categorised perceptual activities as: attending to visual features, attending to spatial relations, and attending to the implicit spaces among the existing spaces. In functional action category, however, they related to design artefacts including issues of interaction, and psychological reactions of people with the artefact. In this coding scheme, the highest action category level—the conceptual action category—corresponded to the semantic activities consisting of categories such as making co-evolutions about previous (physical, perceptual, and functional) actions, set-up goal activities, and retrieving knowledge.

As such, Suwa *et al.* (2000) developed their initial coding scheme by adding some subcategories to perceptual and conceptual actions. They claimed that during a conceptual design process, not only designers synthesise solutions to satisfy the initially given requirements (problem-space), but also they invent new design issues to capture significant aspects of the original problem. Thereby, Suwa *et al.* (2000) asserted that designers need some vehicles for their mind to support their reasoning process. They defined these vehicles as "unexpected discoveries" and "situative inventions". In this model, unexpected discoveries happen when a designer perceives a new aspect of the design artefact, whilst situative invention is led by the mental synthesis of the perceived visual information. They further argued that unexpected discoveries would lead to changes on the current design artefact while situative inventions might give rise to the new requirements to be applied later.

Suwa *et al.* (2000) related unexpected discoveries to the act of finding new aspects of the developing solution-space, and situative inventions to the act of expanding the problem-space. They claimed that the continual perception and conception of the external representations are significant during a conceptual design process since perceptual interaction with one's own sketches serves as an impetus for pushing forward the co-evolution of the solution-space and the problem-space. Thus, in order to evaluate this continuality, they prioritised unexpected discoveries among all other perceptual actions and situative inventions among all other conceptual actions.

Although this coding scheme was not originally designed to study collaborative design works, Kim and Maher (2008) added some new collaborative codes to this scheme. Their collaborative action category consisted of both cognitive synchronisation and gesture actions. In other words, the new format of this coding scheme was capable of capturing designers' collaborative conversations and gestures in order to measure the level of collaboration that they had during the design process.

As such, the coding scheme utilised in this study was adopted from the studies of Suwa *et al.* (1998, 2000), due to their reputation and also the similarity between their studies and this research. The study took the main five categories from Suwa *et al.*'s (1998, 2000) coding scheme and developed its multiplied sub-categories based on the preliminary observations of the designers' actions performed during the experiment. With respect to design collaboration, this study borrowed and adopted Kim and Maher's (2008) codes for collaborative activities. Finally, the proposed coding scheme categorised designers' spatial cognition into five different levels labelled as *'physical-actions'*, *'perceptual-actions', 'functional-actions'*, *'conceptual-actions'*, and *'collaborative-actions'*.

Although no scholars had claimed that the developed coding scheme was the best possible answers for this kind of study, this coding scheme was capable to embrace all the cognitive codes that designers

TABLE 1
Developed coding scheme for 5 action-categories and their sub-categories adopted from Suwa et al. (1998, 2000) and Kim and Maher (2008)

Category		ID	Index	Description
Physical		P	-	Directly related to the P-actions
	D-actions	Da	-	Depicting actions which create or deal with any visual external representation of design
	CreateNew	Dacn	New	To create a new design element or a symbol (drawing circles, lines, textures, arrows, etc)
	ModifyExisting	Dame	New	To edit the shape, size, texture etc of the depicted element
	CreateMask	Dacm	Old	To create a mask area for selecting something
	RelocateExisting	Dare	New	To change the location or the orientation of the depicted element
	CopyExisting	Dace	New	To duplicate an existing element (for digital work only)
	TracingExisting	Date	Old	To trace over the existing drawing
	RemoVeExisting	Dave	New	To remove an existing object or (for digital work only) to undo any command or to turn off
	L-actions	La	-	Look actions which include inspecting a previous depictions or any given information
	InspectBrief	Laib	Old	Referring to the design brief
	TurnonObject	Lato	Old	Turning on the invisible objects
	InspectScreen	Lais	Old	Looking at screen (for digital work only)
	Inspect-sHeet	Laih	Old	Looking at design sheet (for manual work only)
	Inspect3DModel	Lai3	Old	Looking at virtual or physical 3D model while rotating it
	M-actions	Ma	-	Other P-actions which can fall into the motor activities
	MovePen	Mamp	New	To move pen on the paper or board without drawing any thing
	MoveElement	Mame	New	To move an element in the space arbitrarily for finding new spatial relationship
	TouchModel	Matm	New	To touch either physical or virtual model to stimulate motor activities
	ThinkingGesture	Matg	New	Any arbitrarily gesture which motivates thinking about design
Perceptual		Pe	-	Actions related to the paying attention to the visuo-spatial features of designed elements
	P-visual	Pv	-	Discovery of visual features (geometrical or physical attributes) of the objects and the spaces

cont'd Table 1

	NewVisual	Pnv	Unexp.D	New attention to a physical attributes of an existing object or a space (shape, size or texture)
	EditVisual	Pev	Other	Editing or overdrawing of an element to define a new physical attribute
	NewLocation	Pnl	Unexp.D	New attention to the location of an element or a space
	EditLocation	Pel	Other	Editing or overdrawing of the location of an element or a space to define a new physical attribute
	P-relation	Pr	-	Discovery of spatial or organisational relations among objects or spaces
	NewRelation	Pnr	Unexp.D	New attention to a spatial or organisational relations among objects or spaces
	EditRelation	Per	Other	Editing or overdrawing of a spatial or organisational relations among objects or spaces
	P-implicit	Pi	-	Discovery of implicit spaces existing in between objects or spaces
	NewImplicit	Pni	Unexp.D	Creating a new space or object in between the existing objects
	EditImplicit	Pei	Other	Editing the implicit space or object in between the existing objects by editing or relocating the objects
Functional		F	-	Associating visual or spatial attributes or relations of the elements or the spaces with meanings, etc
	F-interactions	Fi	-	Interactions between designed elements or spaces and people
	NewInteractive	Fni	-	Associating a interactive function with a just created element or space or a spatial relation
	ExistingInteractive	Fei	-	Associating a interactive function with an existing element or space or a spatial relation
	ConsiderationInteractive	Fci	-	Thinking of an interactive function to be implemented independently of visual features in the scene
	F-psychological	Fp	-	People's psychophysical or psychological interactions with designed elements or spaces
	NewPsychological	Fnp	-	Associating a psychological function with a just created element or space or a spatial relation
	ExistingPsychological	Fep	-	Associating a psychological function with an existing element or space or a spatial relation
	ConsiderationPsychological	Fcp	-	Thinking of an psychological function to be implemented independently of visual features

cont'd Table 1

Conceptual		C	-	Cognitive actions which are not directly caused a visuo-spatial features
	Co-evolution	Ce	-	Preferential or aesthetical assessment of the P-actions or F-actions
	Set-up Goal activities	Cg	-	Abstracted issues out of particular situations in design representation which are general enough to be accepted via the design process thoroughly as a major design necessity
	GoalBrief	Cgb	Other	Goals based on the requirements of the design brief
	GoalExplicit	Cge	S-inv	Goals introduce by the explicit knowledge or previous cases
	GoalPast	Cgp	S-inv	Coming out through past goals
	GoalTacit	Cgt	S-inv	The goals that are not supported by explicit knowledge, given requirements, or previous goals
	GoalConflict	Chc	S-inv	Goals devised to overcome problems which are caused by previous goals
	GoalReapply	Cgr	Other	Goals to apply already introduced functions in the new situation
	GoalRepeateD	Cgd	Other	Goals repeated through segments
Collaborative		CO		Cognitive synchronisation and gesture actions concerned with group design activities
	Cognitive synchronisation	COs		Cognitive synchronisation to support collaborative work
	Proposal	COcp		Proposing an idea of the problem or a new opinion
	Argument	COca		Supporting or arguing the proposed concept or opinion
	Question	COcq		Asking for a suggestion
	Resolution	COcr		Making a common decision
	Specification	COcs		Identifying existing elements or spaces
	Gesture actions	COCg		Gesture actions to support collaborative works
	TouchGesture	COCgt		Touch any part of sheet, physical model, or virtual model for explaining something
	DesignGesture	COgd		Any large hand movement above the design area for explanation
	PointGesture	COgp		Point to a part of the physical or virtual model or any part of the design for explanation
	ImitationGesture	COgde		To depict any symbol or visual attribute for explanation
	GeneralGesture	COgs		Any general hand movements accompanying speech

produced during the experiments, since it was redesigned and calibrated based on the observation of the design sessions of this study. Moreover, since the consequent coding scheme was quite objective and Suwa *et al.* (1998, 2000) and Kim and Maher's (2008) cognitive models provided clarity for explaining the designers' collective cognitive and collaborative actions, ease of developing hypotheses was the main advantage of the developed coding scheme. The details of the developed coding scheme as well as all action categories and sub-categories are presented in Table 1.

Data Analysis Strategies in Design Protocol Analysis Studies

After segmentation and developing the coding scheme are done, the codes need to be assigned to every segment based on observation of the recorded videos and reviewing the transcribed media. Table 2 is an example of arbitrated data of one of the sessions of the sample design protocol analysis study which is reported in this paper. Analysing design protocols and interpretation starts only after assigning related codes to every segment.

The most common method for interpretation and analysis of both content- and process- oriented design protocols is using statistical methods (Kan, 2008). In particular, Kan (2008) categorised all protocol data and the coded segments into two groups: 1) the qualitative data or categorical (nominal) data, and 2) the quantitative data which concern the duration (time). Based on the distribution assumptions, Kan (2008) proposed two types of analysis for design protocols: *1) descriptive statistics,* and *2) inferential statistics.* Kan (2008) asserted that in protocol analysis studies the purpose of descriptive statistics is to provide a summary of the protocol data and to reveal how the designers spent their time throughout the process. This type of statistics is usually associated with charts and tables for presentation purposes. For instance, Kim and Maher (2008) used descriptive statistics to study the impact of one kind of tangible user interfaces (TUI) on designers' collaborative design behaviours.

Contrary to descriptive statistics, inferential statistics are used when scholars try to test hypotheses to verify a proposed

TABLE 2
Example of the arbitrated data in a design protocol analysis study

Seg	Transcript	P-action	Pe-action	FC-action	CS-action	Gesture
74	A: Why too long?	L.Screen	N.Visual	CoEvoluation	Argument	Design
75	M: this is for exhibition area.	None	None	N.Interactive	Explanation	Point
76	A: 1,2,3,4,5…OK	L.Screen	N.Relation	GoalBrief	Argument	Point
77	M: Open exhibition. This is for gallery.	CreateNew	None	N.Interactive	Proposal	Point

model for designing. For instance, McNeill *et al.* (McNeill *et al*., 1998) used *t-test* to confirm their hypothesis that the design process moves from a design requirement, which is expressed in terms of function to a the given design description in terms of structure. In many cases, hypothesis-testing is also used to compare designers' cognitive and collaborative activities in different conditions (e.g. in Bilda *et al*., 2006; Kim & Maher, 2008; Menezes & Lawson, 2006). *Chi-square* test is another common tool used in the protocol analysis for hypothesis testing. Kan (2008) argued that this test could reveal if the frequency distribution of certain coding categories observed in a protocol is dependent on a particular theoretical distribution. This test is an inferential type of statistical analysis and could be employed for testing hypotheses regarding relationships among different variables and categories.

Correlation tests are other alternatives in testing hypothesis in design protocol analysis when people are trying to propose a new cognitive model for designers' behaviours. For instance, Kavakli and Gero (2002) used a correlation coefficient to obtain the structure of cognitive actions and compared them between expert and novice designers. Furthermore, in many cases (e.g. Bilda *et al*., 2006; Rahimian *et al*., 2011), variance analysis (ANOVA) was used to carry out testing and comparisons among different sets of protocol data to confirm their proposed hypothesis.

Similarly, this study relied on both descriptive and inferential statistics to analyse and interpret the collected data. Graphs and charts were employed in descriptive statistics to explore the meaningful protocols of changes in designers' cognitive and collaborative actions when they transit from one design method to another. The inferential statistics were also employed for testing the assumed hypotheses. The study adopted both types of inferential tests for *'comparing mean value of variables'* and also for *'testing the relationship between variables'*. This will be discussed in the following sections, which will include how the adapted strategies for data analysis helped this study to interpret the findings and provided detailed information regarding designers' collective cognitive and collaborative activities.

Validation and Reliability of Protocol Analysis Studies

Clayton *et al.* (1998) argued that due to the high amount of elicited data through the experiment, such empirical research methods for testing the effectiveness of a design process inherently have high validity and reliability. In addition, they have some guidelines for maximising the validity and reliability of the experiment. They proposed complementing the evidence driven from theory and working models which can increase both validation and reliability of the results. In order to increase the validity of the findings they suggested repeating the experiment by employing multiple participants for at least three times. In terms of reliability, Clayton *et al.* (1998) suggested using paired sampled experiment method in which the same participants perform in both types of the design sessions. Moreover, to controlling learning effect (i.e. performing better in the second trial due to experience learnt in the first trial) during the two sessions (Bilda & Demirkan, 2003), it was suggested to have two different design problems with similar complexity and type (Kim & Maher, 2008) and having at least one month time gap (Clayton *et al*., 1998) between each group's two sessions. In order to prevent any unexpected technical problem, it is strongly suggested by Clayton *et al.* (1998) to refine the experiment system and train the participants prior the commencement of the actual experiment. Finally, the consistency in changes in design process and spatial cognition across the design groups could be another evidence for the validation of the claims of every design protocol analysis study (Kim & Maher, 2008).

Sample of the Conducted Protocol Analysis Experiment

This section presents the sample conducted protocol analysis study to explain how an experiment could be designed in such researches in order to test the proposed new methods of designing through adapting quantitative research methodologies. The purpose of the conducted sample experiment was to compare the efficiency of the proposed Virtual Reality 3D Sketching medium with the traditional methods of pen and paper sketching. The experiment targeted testing the efficiency of the new medium in supporting both cognitive and collaborative aspects of architectural design performed by novice designers. The conducted experiment was guided by van Someren *et al.'s* (1994) guidelines in designing the study in five steps: *1) conducting experiment, 2) transcribing protocols, 3) parsing the design process into segments, 4) developing coding scheme and encoding protocol,* and *5) selecting strategies to analyse and interpret the encoded protocols*.

Development of the Research Instrument

In order to compare the impacts of the proposed 3D sketching design medium on the designers' cognitive activities, the study proposed a simple traditional conceptual design package as the baseline system and a tangible VR-based digital design package as a 3D sketching environment. The experiment focused on designers' collective cognitive and collaborative activities when working on similar design tasks. Three pairs of 5th year architecture students experienced with the traditional design and CAD systems were selected as the participants of this experiment. Each pair was required to complete two design tasks when utilising traditional and 3D sketching design media sequentially. During the experiment, protocol analysis methodology was selected as a research and data acquisition method to explore the effects of the different media on designers' spatial cognition and collaboration.

The baseline traditional conceptual design package comprised of design pencils, pens, butter papers, and simple mock-up materials, e.g., polystyrene as well as drafting tables and chairs. The proposed VR based digital design package consisted of a tablet PC for providing the designers with preliminary design ideations interface and a desktop PC as a platform for the actual digital design process. Commercial software (i.e., Adobe Photoshop™) was installed on the tablet PC to facilitate the layering ability that was available in the traditional sketching system. Therefore, these designers were able to produce preliminary sketches directly on the screen of the tablet PC. The utilised desktop PC was attached to a Six-Degree-of-Freedom (6DF) SensAble haptic device in order to support force-feedback and vibration. The study used an evaluation version of ClayTools™ (integrated with SensAble Haptic device) software as the basic environment for supporting designers' spatial reasoning and modelling activities. Details of both the systems are shown in Fig.2.

Design Tasks

In order to test the effects of the interface on all aspects of the conceptual architectural design, the designers were required to perform in two comprehensive conceptual design sessions for full three hours each. Therefore, during these sessions, designers were asked to undergo all stages of conceptual design, including initial bubble diagramming, developing design idea, and preparing initial drawings. The goal of the first design task was to design a shopping centre with maximum 200000 square feet built up area. The goal of the second design task was to design a culture and art centre with maximum 150000 square feet built up area. In order to make the designers concentrated on design itself, rather than presentation, during both sessions they were required not to use more than one colour in rendering and mock-ups. Some of the examples of the results of the designs performed by the designers are shown in Fig.3.

Experimental Set-ups: Traditional Session vs. 3D Sketching Session

The traditional sessions were held at a design studio whilst the 3D sketching sessions were held at an office which was being used as the VR lab during the experiment. In order to record all of the events during (both) design sessions, two digital cameras and one sound recorder were used. The purpose of the first camera was to record

Fig.2: Traditional (left) and 3D sketching (right) design settings

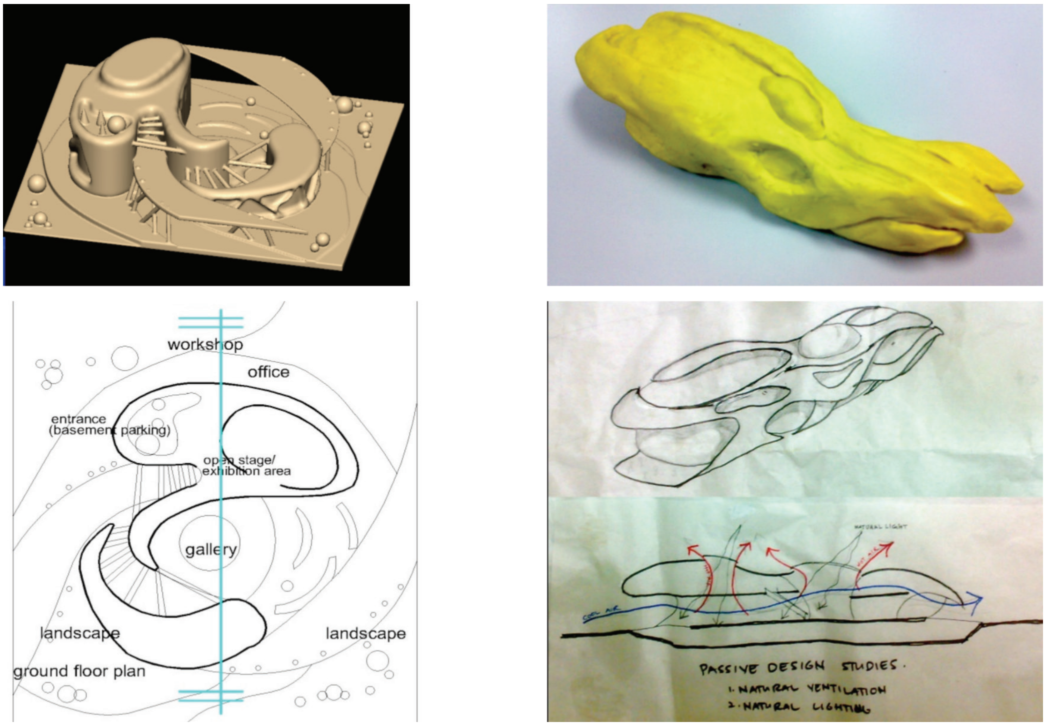

Fig.3: Sample 3D sketching (left) and traditional design (right) outcomes

all the drawings produced during the test. The other camera was set up to record the designers' design gestures and behaviours. Finally, the digital sound recorder was used to record the designers' collaborative conversations. The designers were asked to sit on one side of the table which was facing both cameras. Without interfering with the designers' thinking process, the experimenter was present at both design studio and VR Lab to prevent any technical problem. The explained settings are shown in Fig.4 and Fig.5.

DISCUSSION ON THE MICROSCOPIC ANALYSIS OF THE COLLECTED EMPIRICAL PROTOCOL DATA

In reporting the finding, such protocol analysis studies which relied on the observation of the designers' behaviours as well as the statistical analysis of the encoded design protocols, needed to employ both descriptive and inferential statistics for analysing and interpreting the collected data. In terms of descriptive statistics, graphs and charts could be used to explore the meaningful protocols of the changes in designers' cognitive and collaborative actions. When linked to the cognitive based theories of designing, significant facts regarding the designers'

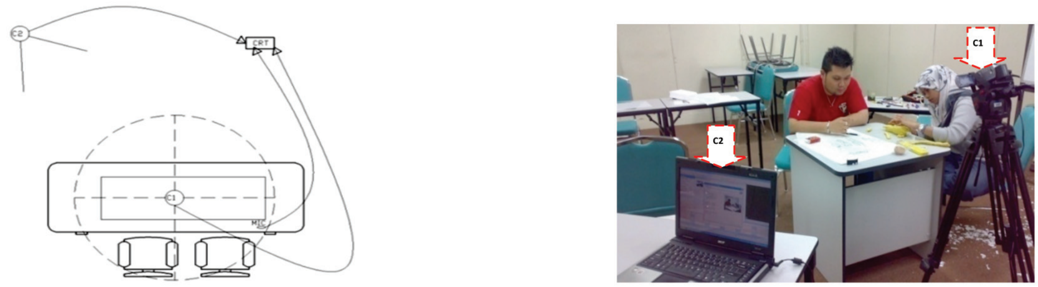

Fig. 4: Experimental set-up of the traditional sessions

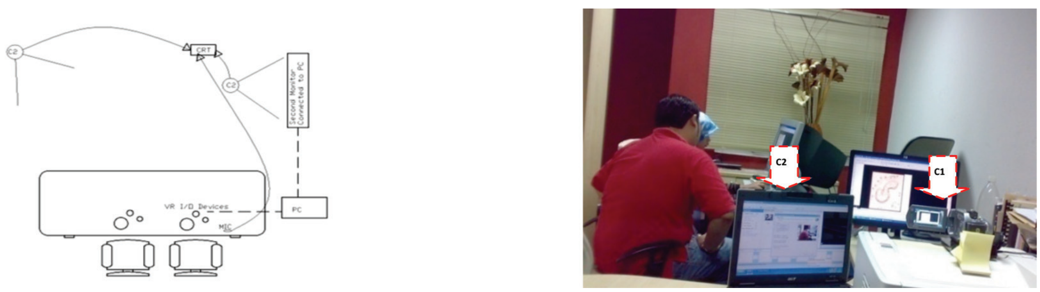

Fig.5: Experimental set-up of the 3D sketching sessions

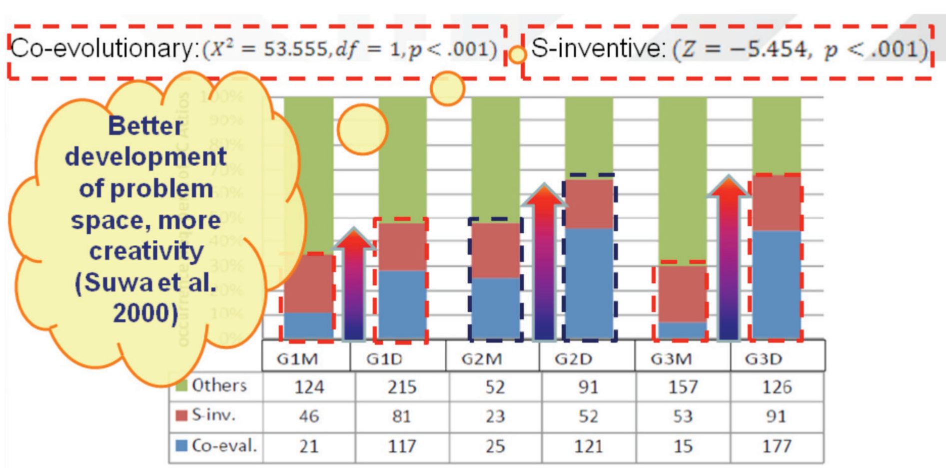

Fig. 6: Occurrence frequency percentage of the designers' co-evolutions (Co-evol.), situative-inventions (S-inv), and the other functional-conceptual (FC) during different design sessions

reasoning procedures were discovered. For instance, Fig.6 illustrates how descriptive data reporting methods were used in the conducted sample protocol analysis study. Fig.6 shows how the normalised bar charts were associated with the seminal theories of design cognition in order to explain the differences in reasoning processes of designers during different phases of design when working with different media. The interpretation of such visual data mainly relies on the occurrence frequency of *"situative-inventions"* (Suwa *et al*., 2000) as well as *"co-evolution"* (Cross & Dorst, 1999) of problem and solution spaces.

Co-evolutionary design model is an approach to design problem-solving which was initially proposed by Maher *et al.* (1996). In this model, the design requirements and design artefacts are formed disjointedly while mutually affecting each other. Cross and Dorst (1999) further developed this model explained the model of design creativity as a *"co-evolution"* of problem and goal [solution] spaces. From a similar perspective, Suwa *et al.* (2000) discussed *"solution-space"* and *"problem-space"* as two interrelated qualities of the design artefact. They related the problem-space to the mental spatial requirements of the design artefact and solution-space to the physical representation of the defined problem-space on design interface. For instance, asking the designers to provide shop lots in a shopping centre as a design brief requirement is a kind of defining the problem-space. However, when a designer draws a rectangle and calls that a 'shop lot', the designer brings the idea from problem-space into the solution-space.

Suwa *et al.* (2000) asserted that *"situated-invention"* of new design requirements could be considered as a key for invention of a creative artefact, since introducing new constraints could help designers capture significant parts of the design problem and go beyond a basic synthesis of solutions which can only suit the initial requirements. They argued that occurrence of situative-inventions is interrelated with the occurrence of "unexpected-discoveries" which are the perceptual activities that could articulate tacit design semantics into visuospatial forms in an unanticipated way. Kim and Maher (2008) combined all these theories and ascertained that occurrence of multiple instances of situative-inventions

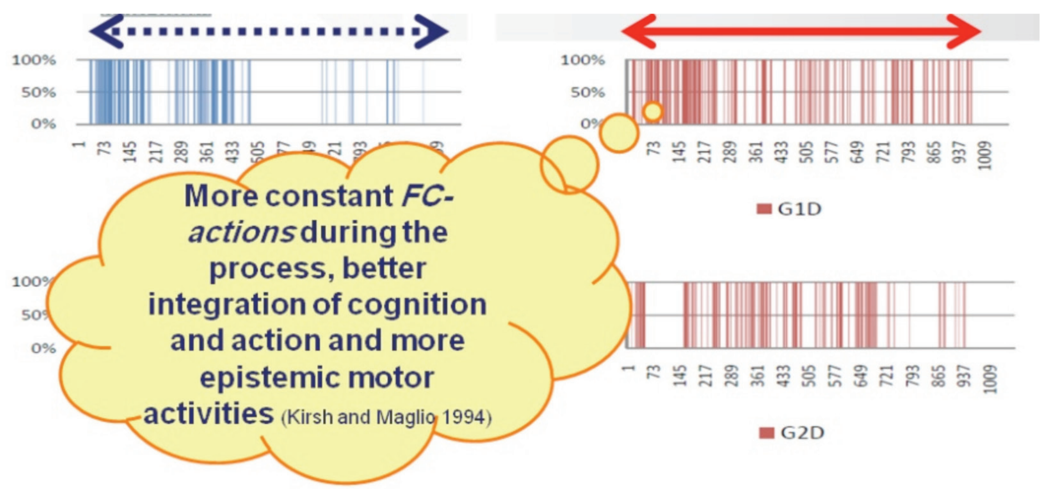

Fig.7: Occurrence frequency scatter bars of designers' functional-conceptual (FC)-actions during different design sessions

and co-evolution of re-interpretations in external representations could lead to more creativity. They also explained how this could introduce new variables for the revision of design ideas and the goal space of design. As could be seen in the coding scheme of this study, such research instruments are objective enough to help design researchers distinguish all these situative-inventions and co-evolutionary activities from normal design actions.

As another example, Fig.7 presents the way that the scatter bars of the occurrence of each type of cognitive activity during different processes were printed. In this example, the changes in the density of the bars in every stage of the process show the consistency and inconsistence of occurrence different design protocols of under different design circumstances. Again, when associated with the seminal theories, this type of analysis is very useful when the researchers aim to validate new theories about designers' cognitive protocols and effects of adopted different design processes or utilised media on cognitive designers' models. The interpretation of such visual information mainly relies on design cognition theories regarding epistemic or pragmatic motor activities (Kirsh & Maglio, 1994).

Fitzmaurice (1996) used definitions of epistemic or pragmatic actions to explain the value of motor activities which are observed in different design interfaces. In this definition, epistemic or pragmatic actions could reveal hidden information which is difficult for mankind to compute mentally. Relying on this theory, Fitzmaurice (1996) asserted that external representations via design interfaces could help designers perform easier, faster and more reliable internal design reasoning. Kirsh (1995, p. 1) described a complementary epistemic activity as *"any organising activity which recruits external elements to reduce cognitive loads. Typical organising activities include positioning, arranging the position and orientation of nearby objects, writing things down, manipulating counters, rulers or other artefacts that can encode the state of a process or simplify perception."* Kirsh (1995) also conducted a basic *"coin-counting"* experiment to test the concepts of epistemic or pragmatic actions. Kirsh (1995) ascertained that epistemic actions where the participants were allowed to use their hands in counting the coins, improved the task quality in terms of completion on time and number of errors. Based on the finding of Kirsh (1995), Fitzmaurice (1996) categorised the benefits of epistemic activities for designers as: 1) decreasing the involvement of memory in mental computation (space complexity), 2) decreasing the number of mental computation steps (time complexity), and 3) decreasing the rate of mental computation error (unreliability).

CONCLUSION

This study was motivated by the issues associated with the emerging complicated global design problems. There are increasing needs for more objective research methodologies in assessing 'new' design strategies, which can not be simply assessed by the conventional self-reporting subjective survey methods. This paper supports an increasing interest in using advanced design research methodologies for analysing the structures and processes of design cognition in order to describe designers' behaviours and performance. It has presented how *"protocol analysis"* can help researchers trace the efficiency of designers' activities during different stages of design process. Using the example of a conducted protocol analysis experiment, the paper explained why the use of quantitative design assessment methodologies is recommended to improve the researchers' understanding of design activities within design schools. The paper has also presented how conducted sample design protocol analysis study encoded design protocols then performed descriptive and inferential statistical analyses on the collected protocol data. The paper further explains how the results of the sample study provided opportunity to analyse designers' cognitive protocols at a microscopic level when relying on the seminal theories of design cognition field (e.g., Cross & Dorst, 1999; Gero & Kannengiesser, 2000; Kim & Maher, 2008; Kirsh, 1995; Kirsh & Maglio, 1994; Suwa *et al*., 2000; Suwa *et al*., 1998; Suwa & Tversky, 2001). In conclusion, taking into account the possibility of extracting valuable information about designers' thinking protocols (Clayton *et al*., 1998; Kan, 2008), this paper recommends the use of such quantitative research methodologies as a new paradigm in the evaluation of new design curricula adapted in rapidly growing Malaysian design schools. With higher accuracy on insights into the cognitive aspects of existing and new design methodologies in Malaysian design schools, design researchers could utilise it as a stepping stone for leveraging research on teaching and learning in architectural design studios in Malaysian universities.

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