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Cognitive transformation mediated by VR 3D sketching during conceptual architectural design process

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Abstract

To optimize the level of cognition and collaboration during conceptual architectural design phase, novice designers need to employ more flexible and intuitive digital media. This paper presents findings of a feasibility study for using VR 3D sketching interface in order to replace current non-intuitive Computer Aided Design (CAD) tools. We use a sequential mixed method research methodology including a qualitative case study and a cognitive-based quantitative protocol analysis experiment. Foremost, a case study research comprising of ethnography for data collection and artefact and protocol analysis for data analysis was employed in order to understand how novice designers make intuitive decisions. The ethnography study documented the failure of conventional sketching methods in articulating complicated design ideas and shortcomings of current CAD tools in intuitive ideation. Moreover, the subsequent artefact analysis affirmed established constructs about advantages and disadvantages of each medium in providing *"solution quality"* and also *"certainty about correctness of solution"*. The case study's findings then became the theoretical foundations for testing the feasibility of using VR 3D sketching interface during design. The latter phase of study evaluated the designers' spatial cognition and collaboration at six different levels: *"physical-actions"*, *"perceptual-actions"*, *"functional-actions"*, *"conceptual-actions", "cognitive synchronizations",* and *"gestures"*. The results and confirmed hypotheses showed that the utilized tangible 3D sketching interface improved novice designers' cognitive and collaborative design activities. In summary this paper presents and documents the influences of current external representation tools on designers' cognition and collaboration as well as providing the necessary theoretical foundations for implementing VR 3D sketching interface. It contributes towards transforming conceptual architectural design phase from analogue to digital by proposing a new VR design interface. We propose that this transformation to fill in the existing gap between analogue conceptual architectural design process and remaining digital engineering parts of building design process hence expediting digital design process.

Keywords: conceptual architectural design, VR, 3D sketching, design collaboration, design cognition

1 Literature review and background problem

This study has been motivated by the existing literature reflecting the shortcomings of current design tools in conceptual architectural design process. The literature on one hand argues that conventional manual sketching interfaces have some shortcomings in articulating new comprehensive global projects (e.g. Madrazo, 1999, Marx, 2000) and on the other hand, it indicates the failures of current CAD tools in replacing the manual sketching interfaces (e.g. Bilda and Demirkan, 2003, Kwon et al.,

2005, Meniru et al., 2003) due to their inherent problems which hinder designers' spatial cognition during the conceptual architectural design process. Hence, there are still parts of design which are handled by freehand sketches (Suwa et al., 1998) while most other parts are being done digitally. This transition is known to interrupt the continuity of a design process (Kwon et al., 2005). However, the integration of whole building design process has since been suggested by Fruchter (1998) since she believes that it can better support collaboration among team members besides having major advantages in decreasing labour and material costs within current comprehensive production procedures. In summary the aim of this research was to facilitate digitization of conceptual architectural design process. This is expected to serve integration of whole building process besides the possibilities for improving designers' cognition and collaboration during conceptual architectural design process. As mentioned earlier this aim was motivated by emerging challenges caused by comprehensive global building projects (Madrazo, 1999, Marx, 2000).

The purpose of this research was to enhance the integration of a whole building process besides the possibilities for improving designers' cognition and collaboration during conceptual architectural design process. This study found some capabilities in new VR technologies to address all the above mentioned problems. In other words, it support the use of a substitute modelling technology that is called VR 3D sketching in order to overcome the inadequacy of conventional manual design tools in articulating complex design ideas and to compensate the inflexibility of current CAD tools in intuitive design ideation. This VR based design interface is defined by the scholars as a design tool which is easy to use as the manual sketching besides providing a highly detailed 3D visualization environment. In defining this design interface Levet et al. (2006) use sketching metaphor and mention that in 3D sketching designers can swiftly produce 3D prototypes to exemplify the 3D objects that they have in mind. The idea of using VR 3D sketching in design is also supported by Kwon et al. (2005) since they believe that this would improve the performance of the computerized design process and speed up the incorporation of engineering requirements during the conceptual phases; i.e. applying the digital format rather than such analogue conventional formats that are currently being used.

To achieve the mentioned aim the study developed the main research question. Afterwards, in order to answer the main research question the study divided it into three Sub-RQs which are to identify: 1) the characteristics of current design media, 2) the collaborative design culture of conceptual architectural design process, and 3) the key enablers in VR 3D sketching methodology that can optimize designers' cognition and collaboration during conceptual design sessions.

2 Research methodology

As discussed above, the aim of this research was to facilitate digitization of conceptual architectural design process in order to enhance the integration of the whole building process besides developing and enhancing the current state of the design interfaces. This was expected to improve designers' cognition and collaboration during conceptual architectural design process. This aim was intended to be achieved by developing a new design methodology based on Schön's (1983a) "reflective practitioner" theory, Fitts' (1964) "motor learning" theory and then verifying its effectiveness with empirical data. Schön's (1983a) "reflective practitioner" theory argues that designers are in a mutual relationship with external representations and are getting reflections from them. Whereas, Fitts' (1964) "motor learning" theory states that tangible interfaces can improve designers' cognitive action. In this case the focus is on the integration of designers' other senses (e.g. the sense of touch) with their visual sense. The point is that the integration of such senses can make design actions epistemic. Therefore relying on both theories, the research seeks for clues of design support tools' quality by investigating design protocols and artefacts.

As per presented, our first and second Sub-RQs respectively refer to the current state of practice utilizing different design interfaces and the existing communication culture among designers.

According to Shuttleworth (2008), case study could be an appropriate research methodology for answering these RQs since the purpose of those RQs is to test theoretical models by using them in real world situations. Case study is basically a qualitative research methodology (Creswell, 2002). On the other hand, the third Sub-RQ refers to the qualities of the designers' cognitive and collaborative actions using a particular design interface, i.e. 3D sketching. For the past two decades, design protocol analysis is the most prevailing research methodology for this kind of design studies (Cross et al., 1996). Based on its strategies in measuring design protocols, Kan (2008) acknowledges protocol analysis as a basically quantitative research methodology. Creswell (2002) named such a research which starts with qualitative approach and continues with quantitative approach as 'sequential mixed method research' approach. Hence, the study follows Creswell's (2002) guidelines in designing the sequential mixed method research by pursuing a single research aim and attempting to answer a single main RQ, while employing multiple research methodologies in answering different Sub-RQs.

In this research, during the development of the theoretical foundations of the study, the employed qualitative approach provided a broad and deep understanding of the current state of design interfaces and interactions during conceptual architectural design phase. In addition, the new empirical assessment techniques which are utilized in this study led to the possibility of investigating design protocols in a quantitatively manner (measures of diversity, time-related events and derived design processes) besides the using standard statistics possibilities when dealing with design protocol data.

The first qualitative part was a case study research which employed ethnography for data collection and artefact and protocol analysis for data analysis. Units of analyses for this part of study were design artefacts of a 2nd year architectural design studio at a local university comprising 37 students and four studio mentors. Taking into account the nature of the building project that they examined, the study adopted judgment sampling method (Kumar, 2005) to choose the sample population among our different studios. Homogenous conditions were expected since all subjects had undergone the same architectural training at the design school and they were all at the same design level. The design project that the studio undertook was a handicraft *arcade* (defined for purposed collection of similar shopping stalls) for a town in the East Coast of Malaysia. The gatekeeper during the data collection phase was the Studio Master of the design studio. This part aimed to answer the first and second research questions by identifying the characteristics of current design media and collaborative design culture of conceptual architectural design process. Consequently, the recommendations of the case study research helped us to develop theoretical foundations of the study.

The purpose of the quantitative part was to provide objective and empirical evidence for the subjective view that proposed VR based 3D sketching interface improves the designers' spatial cognition and collaboration during conceptual architectural design phase. Indeed, the conducted experiment was a comparison on design activities between a VR based simple and tangible interface and a traditional pen and paper sketching interface. Here the traditional sketching method was selected as a baseline to be compared to a proposed 3D sketching design methodology. The purpose was to reveal the cognitive and collaborative impacts of the proposed design system. Five pairs of 5th year architecture students experienced with the traditional design and CAD systems were selected as participants for this experiment. During the experiment, protocol analysis methodology (Dorst and Dijkhuis, 1995, Ericsson and Simon, 1993, Foreman and Gillett, 1997, Lloyd et al., 1995, Schön, 1983a) was selected as a research and data acquisition method. It evaluated the designers' spatial cognition at four different cognitive levels: *"physical-actions"*, *"perceptual-actions"*, *"functional-actions"*, and *"conceptual-actions"*. It also evaluated the designers' spatial cognition in two different collaborative levels: *"cognitive synchronizations"* and *"gestures"*.

The conducted protocol analysis methodology has been employed in order to identify designers' cognitive and collaborative actions and to test the related hypotheses based on the analysis of the encoded protocols elicited through the mentioned actions. This experiment answered the third sub research question hence achieving the third objective. The following sections reflect the outcomes of

both mentioned researches and present the findings and answers for the research questions (Bilda and Demirkan, 2003, Kwon et al., 2005, Meniru et al., 2003).

3 Results and analysis

3.1 Outcomes of the case study research

The conducted case study research listed three dominant types of sketching—i.e. fully manual, mixed, and fully digital—used by the students and their studio mentors. The three groups are as follow: Group 1 (Full Manual Mode—FM) uses only traditional sketching tools and abstract modelling methods, Group 2 (Mixed Mode—MM) started design using traditional methods, but later continue the process utilizing CAD modelling tools and Group 3 (Full Digital Mode—FD) started design in CAD environment and continues finalizing the design with it.

The study employed four dependent variables and three independent variables to answer the first and second Sub-RQs and to identify the supportive characteristics and challenges of current external representation media. The dependent variables were *solution quality, certainty of the correctness of the solution, total solution time* and *experienced difficulty in design problem solving* while the independent variables were fully manual, mixed method and fully digital design sketching modes. This study conducted variance analysis (ANOVA) to check whether there is any significant difference among dependent variables belonging to all independent three groups or not. The results are presented in the following paragraphs.

Based on the results from the selected sample the study concluded that the design solutions by subjects using mixed traditional sketching and CAD modelling tools (MM) produce significantly higher solution quality compared to the other two groups ($n = 37; \rho < 0.05$). On the other hand, the entirely manual sketching subjects have significantly higher solution quality compared to those subjects who solved the problem completely in CAD environment($n = 37; \rho < 0.05$). The subjects who used mixed traditional sketching and CAD modelling tools utilized manual sketching in initial design ideations and employed CAD tools in developing design ideas. Based on the findings this study posits that using CAD tools hinder designers' creativity in the early conceptual design stages. It also posits that conventional manual sketching tools are not so successful in developing design ideas particularly when the artefact becomes complicated.

However, the analysis of the second and third variables triggers more doubts about the adequacy of the conventional manual sketching in complicated design stages. Analysis of the second dependent variable revealed a significant decrease for the certainties of the correctness of the solutions of FM subjects compared to the subjects of the other two groups ($n = 37; \rho < 0.001$). However, the results from the survey show no significant difference among the three groups regarding their total time taken for creating their respective solutions($n = 37; \rho > .05$). It implies that while the MM and FD groups had used 3D prototyping techniques to ensure that various design parts fitted and matched together, the FM group (FM) was not quite successful in convincing designers in this regard.

Since it was impossible to control the protocol size for such a huge observational data in terms of time and number of groups, the study resorted to applying subjective protocol evaluation for *experienced difficulty of the design problem solving* for the observed groups. Based on the subjective protocol evaluation using the narrative stories transcribed from the recorded videotapes, results indicate that subjects who had utilized mixed design media were able to pace their design processes with considerable less difficultly compared to subjects from the other two groups. Our observations noted that the same subjects were able to manipulate free hand sketches—as external representation tools—to solve design problems faster and easier. They were also able to use computational capabilities for solving their communicational problems either within design situations or with other

designers. Results also indicate that the FM group had slightly less difficulty in producing design solutions compared to the FD group.

From the above results, the study found that among the three evaluated sketching support systems, the best external representation methodology comprises of mixing both manual and digital tools. The observations and indicative results illustrate that neither manual sketching tools nor CAD software are the better media for current conceptual design communications. This study posits that design semantic gets lost when manual design fails in articulating explicit design idea while design creativity diminishes when using arduous CAD software. The results support the earlier proposition to develop a 3D sketching methodology in VR in order to fill the gap between creative experimentation and precise manufacturing-oriented modelling supporting an integrated conceptual architectural design process.

3.2 Outcomes of experimental protocol analysis research and conclusions

This study employed a cognitive approach to design process to articulate all aspects of the utilized medium during conceptual architectural design process. Here the traditional sketching method is selected as a baseline to be compared with the proposed 3D sketching design methodology and to reveal the cognitive and collaborative impacts of the proposed design system. The experiment comprised 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 coding scheme,* and *5) to analyze and interpret the encoded protocols*. In encoding the collected data and developing the hypotheses the study categorized designers' cognitive actions into five major action categories as *physical, perceptual, functional, conceptual, and collaborative*. Even though the number of participants which is six people seems somewhat small, the protocols included pairs' verbal accounts concurrently per experiment hence providing adequate data for an empirical exploratory study. Three participant groups are exactly the same number that Clayton, Kunz, and Fischer (1998) suggested for guaranteeing the validation of such Charrette-based experiments.

In our experiment the focus was on designers' cognitive and collaborative actions and the hypotheses were being tested relying on the designers' actions. The codes assigned to the different segments were considered as the units of analysis of this study. Although this experiment was made using three pairs of designers performing six design sessions in total, the experiment provides adequate data for observing overall designingly trends and actions. Besides, this study is guided by Clayton et al.'s (1998) recommendations in validating the results. Moreover, during the exploratory study, the study has revealed consistent improvements in the main five aspects of design sessions and spatial cognition across the three pairs that further validate our claim in this study.

From the empirically collected data, the study found that in 3D sketching sessions the increased integration of the physical actions with mental perceptions and conceptions led to occurrence of epistemic actions to improve the designers' spatial cognition. Besides, relying on the literature (Kirsh and Maglio, 1994) the study posited that the epistemic actions facilitated by the rich interface offloaded the designers' mental cognition partly into the physical world, thus letting them have freer mind to create more design ideas. Moreover, 3D sketching interface improved the designers' perception of visuo-spatial features, particularly in terms of unexpectedly discoveries of spatial features and relationships. Based on outstanding design theories (e.g. Schön (1983a)) the study explained how association between mental cognition with the perception of physical attributes can stimulate creativity and offload the mental load.

In terms of functional-conceptual actions of the design process, the study discovered that 3D sketching interface improved the designers' problem finding behaviours as well as improving their co-evolutionary conceptions of their perceptions and problem findings. Borrowing from Suwa et al.'s (2000) this study called the most important aspect of the problem finding behaviours as 'situative-inventions' and argued how the increased percentage of the co-evolutionary and situative-inventions

actions can lead to improved creativity in 3D sketching design session. Further, it had the same argument about the capability of the co-evolutionary conceptions in increasing design creativity.

Lastly, in terms of the collaborative activities the study has observed that the explicit representation ability which is applied in the proposed 3D sketching interface is capable to motivate the designers to share more ideas together. Moreover, the study explained how this interface is capable to change the type of conversations from ordinary clarifications to new proposals and arguments for development of the problem and solutions space. The emergence of this quality in design conversations can enhance the creativity of the design process (Kim and Maher, 2008).

In conclusion, this study posits that the emerging VR technologies are capable to facilitate some senses beyond the visual aspects of the design artefact by offering a new generation of promising CAD tools which are constantly in touch with designers' cognition and collaboration during conceptual architectural design process. We propose that this format transformation for filling in the existing gap between analogue conceptual architectural design process and the remaining digital engineering parts of building design process. Thus, allowing the enhancement for streamlining of digital design process and facilitating the full design integration as aimed by Fruchter (1998). Herewith, it is envisioned that these findings can help the development of cutting-edge information technologies for design or education in the architectural field. Moreover, results will guide in the creation of future professional training programs to enhance capacity and capability of multidisciplinary professionals in using digital interfaces due to increasing global practice.

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