A method to investigate design cognition in virtual environments

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ABSTRACT: High-bandwidth communication and leading-edge design technologies offer promising innovations to the Architecture Engineering Construction industry. Because, these advance technologies reduce the reliance on co-presence and address the challenges of being in distant locations. Although there is a variety of research on collaborative design that examines the way in which designers work and collaborate, it is also not clear that whether the perceiving and acting in the 3D virtual worlds would provide better designing and collaboration experiences through the augmentation of spatial cognition. The paper commences with a comprehensive analysis of a wide variety of newly emerging technologies supporting collaborative design and different modes of design representation. Then the paper presents a methodology of a future study to investigate human cognition in different high-bandwidth collaborative environments. The outcomes will lead to a more critical understanding of how collaborative design can be facilitated, more particularly, how designer collaborate and interact with the external design representations using leading-edge design technologies.

Keywords: Collaborative design, design cognition, protocol analysis, design technologies

INTRODUCTION

Current technological developments are offering new collaborative design environments to designers. Design thinking and design representations have changed with the introduction of digital tools such as digital sketching devices, 3D modelling applications, rendering engines, multi-user 3D virtual worlds and collaborative virtual environments. In the past two decades, a variety of disciplines have participated in developing, implementing and testing information technology tools that are designed to address human collaboration at work, commonly known as Computer Supported Collaborative Work (CSCW) systems. Although there is a variety of research on collaborative design that examines the way in which designers work and collaborate in their normal working environments using traditional and digital media, it is still not yet clear how different types of design environments affect designers’ interaction with the design representation, and what the cognitive benefits are of representing the design ideas at higher levels of realism, in comparison to higher levels of abstraction. It is also not clear that whether the perceiving and acting in the 3D virtual worlds would provide better designing and collaboration experiences through the augmentation of spatial cognition.

There are several studies that explore different aspects of Computer Supported Collaborative Design (CSCD), such as examining the effects of computer mediation on design communication (Gabriel 2000) and on design collaboration (Vera, Kvan et al. 1998) and the impact of virtual environments on collaborative design (Maher, Bilda et al. 2006). Although these studies provide extensive knowledge about the ways in which architects communicate and design in digital environments, there is still insufficient evidence about the way architects collaborate in both co-located environments and remote digital environments, and how their cognition and their interactions with the design representations could change when they move into different kinds of remote environments. This study follows up the previous collaboration study [Blank for review] to investigate the implications of location and representation modes on designer’s cognitive activities in collaboration content. The paper commences with a comprehensive analysis of a wide variety of newly emerging technologies supporting collaborative design and different modes of design representation. Then the paper presents a methodology of a future study to investigate human cognition in different high-bandwidth collaborative environments. The understanding of human design cognition is clearly one of the key resources for system developers to create effective and efficient design systems.

The significance of the present research falls into two categories: (1) providing a knowledge that will help designers to shape the decision to use a particular technology or application, and (2) providing knowledge that will help the software developers to build better systems that facilitate collaborative design.

1. STUDYING COLLABORATIVE DESIGN

To date research has been limited in the acquisition of an understanding of the reasoning heuristics used by designers working in the context of functioning (real world) design teams. Also there is limited understanding of how design teams actually function and what strategies individuals need to acquire in order to facilitate the level of cooperation and interaction necessary for effective participation and contribution to these design teams. Literature documenting research conducted, to date, is primarily focused on homogenous disciplinary teams in a laboratory environment. The teams documented in the research were also working on problems within a limited time frame and the participants in the team being students or recent graduates (Cross and Cross 1996). The process of communicating design ideas requires multifarious strategies. To effectively monitor and analyse this activity the methodology requires the consideration of both verbal and visual interactions.

1.1. Design Cognition and modes of design representation
During the designing activities, possible design solutions may be generated, elaborated and evaluated. Because of the limitations of human capacity (or the working memory) (Miller 1956), designers rely on the external design representations as accessible data storages that reduce the information-processing load. In the field of psychology, Cognitive Load Theory (CLT), as defined by Sweller (1988), points out that optimum learning occurs in humans when the load on working memory is kept to a minimum to best facilitate the changes in long-term memory. CLT assumes that working memory is connected to an unlimited long-term memory (Baddeley 1992). Working memory, especially for instructional designers, is limited to about seven items or elements of information at any one time (Miller, 1956; Baddeley, 1992). Long-term memory is the repository for more permanent knowledge and skills and includes all things in memory that are not currently being used but which are needed for understanding (Bower 1975). Studies show that design externalisations that are off-loaded designers’ mental capacity facilitate increasing the cognitive abilities (Norman 1993) by allowing designers (1) to record the design thoughts, and (2) perform a “conservation with the materials” (Schön and Wiggins 1992) and (3) facilitating external tokens for the “design moves” (Goldschmidt 1996) that must otherwise be kept in mind.

In cognitive research, designing has usually been considered an individual mental process. However, with the recent developments of communication and information technologies and with the extensive use of these tools in designing, understanding the collective design situations has become necessary. Recent research on design has defined cognitive factors as drawing attention to the collaborative nature of designing. Those studies define the qualities of a good collaborative design process in terms of “communication behaviour and communication environment” (Kvan et al. 1997) pointed out that as collaborators come together in design, the nature of their activity does not change, since collaboration still requires a designer to attend to design as an individual tasks, as well as collaborating. Similar to Kvan et al.’s view, we consider that understanding collaborative design activity requires understanding an individual’s design activity. Suwa et al. (1998) examined the cognitive processes of individual designers who were working on a design task using freehand sketches. They looked at four cognitive levels: physical, perceptual, functional and conceptual. Suwa et al.’s (1998) coding scheme has two benefits. First, design actions are definable in a systematic way using verbal design externalisations which is the foundation of analysis of how particular types of actions contribute to developing key design ideas. Second, the scheme provides evidence of how designers cognitively interact with their own sketches.

This research adopts and further develops Suwa et al.’s (1998) design cognition coding scheme which only focused on individual designers’ sketching activities. Further developments of the coding scheme allow us to examine intensely the physical and perceptual aspects of design cognition, as well as idea generation processes in virtual environments (see the initial coding scheme).

**Visuo-spatial reasoning of design representations:** Designers employ external representations concurrently, that is, through at various types of sketches, physical and digital models, diagrams, graphs and notations. The interaction with the design representation, particularly sketching, was seen to represent mental activity, and the complementary relationship between two forms of representation, that is, verbal-conceptual and visual-graphic was viewed as one of the key concepts of design cognition (Akin and Lin 1995; Goel 1995). Akin (1982) pointed out the importance of the external design representations that facilitated the formulation of a mental representation of a design idea as well as the communication of design ideas. Akin (1982) said that: “[…] design consists of a series of representations to one’s mind, or to the minds of one’s co-workers, clients, user groups. […] the mind has its own internal representations in order to communicate through external representations.”

That is, since we cannot as yet directly communicate our internal representations and thoughts, we must rely on the external representations.

External design representations facilitate a dialogue of the designer between her/himself with the design materials (Schön and Wiggins 1992). According to Schön’s theory, design is a “reflective conversation with situation”. Problems are actively set or “framed” by designers, who make “moves” by using a spatial-action language (external design representations). Consequently, Lawson (1997) highlighted that the designer had a conversation with the drawing. The term “conversation”, referring to the designers’ internal processing, included reflective evaluation, exploration of ideas and modification of the ideas (Schön 1983; Goel 1995). Goldschmidt (1994) suggested a similar interaction with the external design representation that utilised visual thinking to deal with pictorial properties of design concepts. She divided design process into moves and arguments that had two types: (a) “seeing as” and (b) “seeing that”. The designer was “seeing as” when s/he was using figural or “gestalts” argumentation, and when “seeing that”, the designer advanced non-figural arguments pertaining to the entity that was being designed. She said that the process of sketching was a systematic dialectic between the “seeing as” and “seeing that” reasoning modalities.

For communicating design ideas to the designer her/himself or to others, designers rely on external design representations. Researchers have studied how designers used design representations to facilitate design thinking, and the relationship between the design process and design outcome has been studied (Atman and Bursic 1998). Ullman et al. (1990) reported that sketches had different levels of abstraction and provide an external memory to aid the designer. In the protocol studies, Kavakli et al. (1998) confirmed that designers sketched objects part by part rather than as a whole. Others suggested that sketches were often used when designers were performing tasks in which they were restructuring images rather than combining parts to make a new image (Verstijnen and Hennessy 1998). In the engineering domain, Cardella et al. (2006) confirmed that external design representations supported every aspect of the student designer’s design process. External representations, sketches in particular, serve as visual aids for design thinking in a variety of ways (Laseau 1989). Architects sketched and examined the sketches to discover visual cues that suggested ways to refine and revise the design ideas (Suwa and Tversky 2002). This cycle-sketch-inspect-revise was similar to Schön and Wiggins’s (1992) reflective conversation with oneself.

Most of the above views are based on the studies that examine designers’ sketching activity. In our study, sketching is also the baseline for characterising the changes in designers’ visual reasoning of the external design representations while using different virtual environments. The external design representations (sketches and models), and designers’ interaction with them and with their surrounding space which has not been previously well understood are investigated in this research.
Tversky (2005) defined four types of space in which human activities occur: (1) the space of the body, (2) the space around the body, (3) the space of navigation, and (4) the space of external representations. Each of them is experienced and conceptualised differently. The space of the body has a perceptual side, the sensations from outside and inside the body, and behavioural side, the actions the body performs. The space around the body includes the space in which it acts and sees, including surrounding objects. The space of navigation is the space for travel, depending on the knowledge and memory, not the concurrent perception. Finally, the space of external representations includes a space on paper meant to represent an actual space, as in a map, diagram or architectural drawing (Tversky 2005). In the field of psychology, studies show that diagrams and models promote participants to take the perspective of a character surrounded by objects (Bryant and Tversky 1999). In their study, Bryant and Tversky (1999) pointed out that with models, participants adopted the character’s perspective, and with diagram, participants took an outside perspective. We are interested in the views of the designers when they are designing in the physical and the virtual space and how the space around the body (physical and virtual) affects their interactions with the design representations. Another dimension of the research examines the designers’ reasoning on the visuo-spatial representations that “captures visuo-spatial properties of the world” (Tversky 2005). This includes visual and spatial information. The spatial relations include the properties that are “close or above or below” in the world preserve those relations of the representations. The visual information includes static properties of objects, such as shapes, textures, colours, or between objects and reference frames, such as distance and direction (Tversky 2005).

The assumption of this research is that because of this multidimensional presence of the body in virtual environments, there will be differences in designers’ perception and visual reasoning on the visuo-spatial properties of the design representation. This phenomenon has not been studied in the field. Based on the above views, this research is concerned with (1) the reasoning of the visuo-spatial features of the external design representations, and (2) the designers’ interactions with the surrounding design space. Thus, the initial coding scheme contains categories to measure those aspects of the research.

1.2. Communication and design collaboration

Technological innovation has had a major impact on the world of design, it is not only an outcome of the design process, but also provides opportunities and options for the designer. Technology has not only provided opportunities but it has also contributed to the complexity of many design processes. In the industrial world there often exists the need for large teams of designers to work collaboratively in the production of large or complex projects. In such situations Design Teams are formed. The complexity of the problem demands that the team comprise individuals who have training and experience in a variety of design disciplines. These discipline areas, depending on the design project, could include designers from a range of design fields, e.g. electrical engineering, industrial design, architecture etc. Lawson, using the example of architects, demonstrated the importance of collaboration to their role as designers:

An examination of professional diaries is likely to show that most architects spend more time interacting with other specialist consultants and with fellow architects than working in isolation............[1997, p.184].

An important consideration in the organisation of a Design Team is the process of re-organisation of knowledge, attributable to participation in these teams. The re-organisation of design knowledge most frequently occurs at design team meetings where designing involves interaction between the team members. It is in the activities of these meetings that ideas of individuals become shared understanding of the team. Consequently, as a result of a team’s design meetings it would be expected that an individual’s knowledge, established prior to the meeting, would change and be augmented as a result of the interactions and experiences of participation in the meeting.

The issue which impacts most significantly on the process of reaching shared understanding, through the design discussion in the team, is the ability of team members to communicate their design ideas with other members of the team. The ability to effectively participate in the forum of a design team unquestionably requires an ability to communicate design ideas and discipline specific information. The study, reported in this paper, identifies the diversity of communication strategies, which contribute to effective communication within the design team context.

1.3. Empirical studies of distributed design collaboration

Collaborative design, as conducted by Design Teams, is described by Cross and Cross (1994) as consisting of the activities of roles and relationships, planning and acting, information gathering and sharing, problem analysing and understanding, concept development and adoption and conflict avoidance and resolution. In a single designer’s brainstorming activity, the same person formulates questions and gives answers concerning different aspects of the problem on all design issues, from aesthetics to functionality. However in team design, circulation and sharing of ideas is paramount to the process of design, specifically in the situation of Design Teams. Valkenburg and Dorst’s (1998) study observed different design behaviours in teams, and propose that the context a team creates is very important in the design process. An example of this situation is in engineering-oriented design professions where it is more common to generate ideas within a group of colleagues, as in a brainstorming session. Goldschmidt’s (1994) comparison of the behaviour and performance of the individual with those of a team found that the individual designer acts like a unitary system that resembles the team. Goldschmidt’s study (1994) provides two issues for consideration regarding the interaction of individuals within a team in a collaborative process: (1) when a team acts together, implicit or explicit roles are created for the team members, along disciplinary or behavioural lines, and (2) each designer in a team develops an expertise so that strongest capabilities of each individual contribute towards the best results. Goldschmidt’s (1994) “acting together” and “contributing” imply communicating. Valkenburg (1998) shows that individual designers have to adjust their personal understandings about the design content to achieve a shared understanding, implying that communication behaviour involves the psychological modes and reactions of the team members, shared understanding, shared language, general awareness of others, co-operation etc.

2. EMERGING COLLABORATIVE DESIGN TECHNOLOGIES

This study concerns the roles of locations and modes of design representations in collaborative design. Advancement in the development of design technologies has enabled collaborative design from the traditional approach of designers being co-located to be remotely distributed, using design representations ranging from digital sketches, digital 3D models.
and Augmented Reality (AR). This study aims to examine and compare four typical settings for collaborative design: (1) the traditional co-located hand sketching; (2) remote sketching; (3) 3D virtual worlds for remote design collaboration; and (4) co-located 3D design enhanced with AR. The traditional hand sketching is most familiar to designers, which has an important role in design professions with a very long history. In comparison, the other three settings for collaborative design are only recently made available to designers due to the emergence of new design technologies. This section will present the technologies that support the last three settings for collaborative design: digital sketching devices, collaborative 3D virtual worlds, and AR.

2.1 Digital sketching: Digital sketching devices such as VR Sketchpad and SEED-Config interpret the freehand drawings and uses these drawings in creating digital design representations. This allows designers to generate design representations based on sketch diagrams for spatial partitions such as walls, columns, and furniture on a 2D floor plan. These digital sketching devices allow designers to create graphic symbols by drawing examples into the system using input devices such as a pen and a tablet. Using these symbol libraries the designers then simply draw sketches to indicate the placements of design elements. The colours for these items can be specified by the designers to distinguish from each other. The digital sketching devices use this information with the sketches to create design representations accordingly. These symbol libraries are often personalised to each designer which the systems then provide meanings and context in some systems perform geometry translations, for example, from 2D sketches to 3D scenes. However, the majority of digital sketching devices remain operating on the 2D level. The context in which the systems can be used depend on the personalised libraries. Collaborations that are possible on these systems include typical design scenarios such as architectural conceptual design, interior layout and so on.

2.2 Collaborative 3D virtual worlds are networked environments design using the place metaphor. Popular 3D virtual world platforms such as Second Life, Active Worlds and others that based on game engines support synchronous communication, shared 3D modelling and the visualisation of designers. Driven by today’s global economy, designers often collaborate with distant counterparts. Nowadays it is very common to see international operations on global design projects. Traditionally, this requires significant amounts of time and financial investments on relocating human and design resources, which can often cause unexpected delay and operational costs to the project lifecycle. For the AEC (architecture, engineering and construction) industry, the advancement of 3D virtual worlds and the proliferation of high bandwidth network technology have shown great potential in transforming the nature of remote design collaboration. With the supports of collaborative 3D virtual worlds, designers can remotely collaborate on projects without concerning the barriers of location and time differences. With high-speed Internet, real-time information sharing and modifications of large data sets such as digital architectural models and building information become possible over the World Wide Web. Distant design collaboration can significantly reduce the relocation costs and help to increase the efficiency in global design firms. Further research development of such systems, for example, DesignWorld (Maher et al 2006) supports remote communications, collaborative 3D modelling and multidisciplinary building information sharing. Similar to many CAD modelling tools, the traditional representations of designs in 3D virtual environments focus on geometric forms (Gu and Maher 2002). Some researchers argue that this lower level of representations can be inadequate to support sophisticated design collaboration where the design team communicate, develop and externalise architectural concepts that are often far more complex than 3D geometrics. In the latest development of 3D virtual worlds, we also see the application of agent models in representing designs in 3D virtual worlds (Maher et al 2004; Smith et al 2003). In the context of computing, agents as intentional software systems operate independently and rationally, seeking to achieve goals by interacting with their environment (Wooldridge and Jennings 1995). Agent-based computing has recently become important for Internet applications, drawing on ideas of artificial intelligence and artificial life. These agent-based developments aim at integrating artificial intelligence to 3D virtual worlds to enhance the interactions during remote design collaboration.

2.3 Augmented Reality (AR), which appears in the literature usually in conjunction with the term Virtual Reality (VR), is a technology or an environment where the additional information generated by a computer is inserted into the user’s view of a real world scene (Milgram Colquhoun 1999; Azuma 1997). More fundamentals regarding AR concept and technology can be found in (Barfield and Caudell 2001). AR technology is envisioned to improve the current state-of-the-art of design representation and visualisation by seamlessly merging the two domains - virtual and physical - together. Augmented Reality technology holds great potential to improve design representation, avoid defects, shorten design time in collaborative design activities. Recent advancement in computer interface and hardware power has fostered AR prototypes for various design applications. However, most of these lab-based prototypes were investigated by computer science/engineering societies which selected design as testing areas for proof-of-concept. Due to the lack of in-depth understanding of design practices, these efforts could hardly progress beyond the lab-phase to eventually become a usable system for practical operations. AR has nowadays matured from a pure technology-bases research field into certain practical industrial applications, but until now it has not been implemented and tested as an application by designers. AR has had a relatively slow transition into the design sector. Military, advanced manufacturing and entertainment users were comparatively early adopters of Augmented Reality. Lab-based applications of AR in the design domain include the ones for architectural conceptual design (Seichter 2003; Aliaaksyeu et al 2006), urban planning (Seichter 2004; Broll et al. 2004), individual mechanical design detailing (Dunston et al. 2002; Dunston and Wang 2005), architectural design (Dias et al. 2002), steel erection planning (Yabuki et al. 2006), collaborative design (Wang et al. 2003; Schmalstieg et al. 2002), etc.

3. AN APPROACH FOR INVESTIGATION OF DISTRIBUTED DESIGN COGNITION

This study is concerned with collaborative design using high bandwidth communication technology and leading-edge design tools. High-bandwidth collaboration offers the opportunity for Australian AEC (Architecture, Engineering, Construction) industry to become globally competitive, because it reduces the reliance on co-presence and reduces the problems of being in distant locations. The results of our previous study show that each high-bandwidth design environment facilitates different ways of designing and interaction with the design representation (Gul, 2007). The
changes in the collaboration behaviour have two folds based on the effect of location and the types of design representation:

- the effect of being in the same location: co-located and remote. Being in the same location and sketching on paper increased the designers’ iterations in the design process actions. The designers stayed in the problem-framing, the idea generation and the synthesis of ideas processes, in which their attention shifts changed quickly. In contrast, in the remote designing, the designers had the situation of immediacy to construct the design representation, rather than exploring alternative design solutions. They concretised their design solution without much iteration in the design process actions. They decided on a particular design idea and constructed it, demonstrating longer attention spans.

- the effect of the type of external representations: sketching and 3D modelling. There are similarities between co-located and remote sketching, and there are differences between sketching and 3D modelling. The sketching (paper and remote) supported the designers’ collaborative activities more than 3D modelling did. In sketching, the designers stayed in a co-design situation, wherein they negotiated and critiqued, staying in high-level design ideas. The designers produced representations through the “create” and the “write” actions in shorter spans, thus allowing them to focus on the visual features of the representation in sketching. In contrast, in the 3D modelling, the designers stayed in the distributed design situation, where they worked on the modelling individually and came together for the negotiation and evaluation, staying in low-level design ideas. The designers created the 3D model through the “continue” action in longer spans, thus allowing them to focus on the spatial relationships of the 3D objects.

Based on the above findings, the research focuses on the above two key aspects when designers move from:

1. Co-located designing to remote designing, and
2. Sketching to designing in 3D mode, as shown in Table 1.

### Table 1 Research Matrix

<table>
<thead>
<tr>
<th>Representation</th>
<th>Location</th>
<th>Remote Sketching (RS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketching</td>
<td>Face to face (FTF)</td>
<td>(using pen-based digital systems, such as SmartBoard, and Mimio)</td>
</tr>
<tr>
<td>Sketching</td>
<td>(baseline: using pen-paper)</td>
<td></td>
</tr>
<tr>
<td>Designing in 3D mode</td>
<td>3D virtual worlds (3D VWs)</td>
<td>(using augmented reality bench-top systems)</td>
</tr>
<tr>
<td>Designing in 3D mode</td>
<td>3D VWs (using desktop)</td>
<td></td>
</tr>
</tbody>
</table>

Based on the matrix above, the present research investigates the followings using protocol analysis:

1. Understanding the changes in the design cognition when designers move from co-located designing to remote designing and sketching to designing in 3D mode, in particular what are the changes in design cognition and visuo-spatial reasoning of the design representation.
2. Understanding the changes in the communication when designers move from co-located designing to remote designing and sketching to designing in 3D mode, in particular what are the changes in design communication and communication skills.

### 3.1. Protocol analysis

In this research project we will identify similarities and differences in collaborative design behaviour in different virtual environments using protocol analysis. Protocol analysis that allows the characterisation of the processes in designing has been used in different design disciplines. Early studies focused on protocol’s verbal aspect (Ericsson and Simon 1984). On the other hand, later studies acknowledged the importance of the design drawings that are associated with the design thinking which can be interpreted through verbal descriptions (Akin 1986; Suwa, Purcell et al. 1998). The protocol analysis, which is a qualitative approach, allows us to measure the changes that can be counted by the coding scheme.

In this research, unlike the think-aloud and retrospective protocols, the design dialogues and actions, which can be considered as different from the individual design externalisations, are the context. To a certain extent, in the present research, our view of analysing the design dialogues is the adaptation of the speech acts theory. The theory refers to the socio-cognitive aspects of the dialogues (Austin 1962; Searle 1969). According to the theory that speaking is far from being a simple information transformation, it is also a way of acting in the world and acting with others, it is a way of defining structures for exchanges and transactions between partners (Darses, Detienne et al. 2001). Thus the analysis of the designers’ communication has the potential to reveal the nature of the design cognition and mental processes of designers.

### 3.2. Coding scheme

The basis for the development of the coding scheme is a consideration of the expected results of the study. The expected result of the study is that the types of representations and the location of designers will change the ways in which designers’ reason and communicate. Thus, measuring the changes in the design cognition, and communication are necessary. The first step in the development of the coding scheme is the literature search. We reviewed existing coding schemes in the design studies, and then borrowed and adapted the categories to measure the changes in the above two aspects. Secondly, through the coding of the experiment data, new codes to the initial coding scheme will be added to capture different aspects of the collaborative design activity. Thus the initial coding scheme will evolve through the analyses of the visual and verbal data. The initial coding scheme of the research has two main categories: (1) design cognition and (2) communication, as shown in Table 2 and 3. The design cognition coding scheme refers to verbal and visual design protocols that have direct relevance to designers’ cognition to solve a particular design problem. This coding scheme is adopted from Suwa et al.’s (1998) design cognition coding scheme. In addition, these categories also
Table 2 Design Cognition coding scheme

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>*Realisation actions: create, continue, delete, write based on definition in (Gul, 2007)</td>
<td>Drawing actions, modelling actions</td>
</tr>
<tr>
<td></td>
<td>*Other physical actions</td>
<td>Move a pen or navigating an avatar, move elements, gesture</td>
</tr>
<tr>
<td></td>
<td>*Inspect representation</td>
<td>Visual analysis of the representation using different view points, drawing perspective from different point of view</td>
</tr>
<tr>
<td>Perceptual</td>
<td>Attend to visual features of elements</td>
<td>Shapes, sizes, textures</td>
</tr>
<tr>
<td></td>
<td>Attend to spatial relations among elements</td>
<td>Proximity, alignment, intersection</td>
</tr>
<tr>
<td></td>
<td>Organise or compare elements</td>
<td>Grouping, similarity, contrast</td>
</tr>
<tr>
<td></td>
<td>*Calculations based on definition in (Kirsh 1995)</td>
<td>Counting, ordering, re-arranging</td>
</tr>
<tr>
<td></td>
<td>*Self referencing: egocentric-allocentric based on definition in (Gul, 2007)</td>
<td>Using own body-local elements for referencing (on my right/left/back/front), using global elements for referencing (north/south/sun, the corner of the building etc.)</td>
</tr>
<tr>
<td>Functional</td>
<td>Explore the issues of interactions between artefacts and people/nature</td>
<td>Functions, circulation of people, views, lighting conditions</td>
</tr>
<tr>
<td>Conceptual</td>
<td>Make preferential and aesthetic evaluations</td>
<td>Like-dislike, good-bad, beautiful-ugly</td>
</tr>
<tr>
<td></td>
<td>Set up goals</td>
<td>Setting goal for her/himself or assigning goals to others</td>
</tr>
<tr>
<td></td>
<td>Retrieve knowledge</td>
<td>Recalling past knowledge</td>
</tr>
<tr>
<td></td>
<td>*Solution-move: progress or change based on definition in (Gul, 2007)</td>
<td>Proposing new ideas, developing the same idea further, vertical moves-proposing alternative ideas to an existing one, lateral moves</td>
</tr>
<tr>
<td></td>
<td>*Re-formalisation</td>
<td>Reconceptualising the design solution</td>
</tr>
</tbody>
</table>

Additional codes to Suwa et al.’s coding scheme (Suwa, Purcell et al. 1998)

The initial communication coding scheme includes six sub-categories, as shown in Table 3.

Table 3 Communication coding scheme

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Externalisation</td>
<td>Verbal and visual design externalisation</td>
<td>Talking with each other—drawing or/and modelling to express ideas</td>
</tr>
<tr>
<td>Communication content</td>
<td>Design, management, presence of each other, actions of each other, technology, social</td>
<td>Looking at the content of the discussion</td>
</tr>
<tr>
<td>Design exchanges</td>
<td>Low-level vs high level based on definition in (Vera, Kvan et al. 1998)</td>
<td>Looking at the level of the design exchanges</td>
</tr>
<tr>
<td>Collaboration mode</td>
<td>Meeting-individual based on definition in (Kvan, West et al. 1997)</td>
<td>Working together or alone on the creation of the representation</td>
</tr>
<tr>
<td>Shared activities</td>
<td>process-related and content-related activities</td>
<td></td>
</tr>
<tr>
<td>Skills</td>
<td>Core skills based on work (Salas, Burke et al. 2000)</td>
<td>Decision making, performance monitoring and feedback, coordination, shared situational awareness, etc</td>
</tr>
</tbody>
</table>

The data of the study will consist of a continuous stream of video and audio that has two sources, the designer 1 and designer 2. Since the aim of the research is to investigate the verbal and visual design protocols in the collaborative design context, there is a need for a thorough investigation of each designer’s externalisations. Consequently, the two major segmentation rules, which are the utterances-based segmentation method (Gabriel 2000; Maher, Bilda et al. 2005) and the actions-and-intentions based segmentation method (Gero and McNeill 1998), are combined in this study. These segmentation rules are considered as the most beneficial ones for the study, since the occurrences of actions/intentions and the verbalisations change quickly as architects draw/model and communicate.

4. FUTURE WORK

This study is concerned with collaborative design using high bandwidth communication technology and leading-edge design tools. High-bandwidth collaboration offers the opportunity for Australian AEC industry to become globally competitive, because it reduces the reliance on co-presence and reduces the problems of being in distant locations. The outcome of the project is the development of knowledge of the impact of new technologies on collaborative design which can lead to a more critical understanding of how collaborative design can be facilitated, and how architects design collaboratively and interact with the external design representations while using virtual environments. The next step is to conduct the experiments and gather information of design cognition for the analysis of designer’s behaviour while they are working on several design environments. Understanding human cognition is clearly one of the key resources for system developers to create effective and efficient design systems. This knowledge will also contribute...
References


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