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THE IMPACT OF DIGITAL DESIGN REPRESENTATIONS ON SYNCHRONOUS COLLABORATIVE BEHAVIOUR

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SUMMARY: *Recent technological developments in Human Computer Interaction (HCI) 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, 3D modeling applications, rendering, multi-user 3D virtual worlds and collaborative virtual environments. The aim of the study is to identify similarities and differences between remote digital sketching and 3D modeling in virtual environments, in order to have a better understanding of the impact of design representation on design collaboration. We report the results of an experiment using protocol analysis. Our analysis shows that the designers demonstrate different collaborative cognitive actions in the remote sketching and the 3D modeling environment. The results of the study with regard to the research objectives are discussed.*

KEYWORDS: *Design representation, design collaboration, digital sketching, 3D modelling*

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1. INTRODUCTION

Employing Collaborative Virtual Environments (CVEs) has been of great popularity in order to facilitate creativity, computation and effectiveness of design in geographically distributed multi-user scenario. CVEs act as communication spaces and shared databases, supporting information exchange and indirect - direct interactions among team members. Recent developments in HCI and virtual worlds have lead to 'being there' in mediated environments that support synchronous collaboration. Being there 'the experience of presence' in a collaborative context is associated with providing clues of awareness of others and a display of 3D objects that appear to surround the people collaborating. In virtual worlds, the sense of presence is achieved by including avatars in the environment that provide information about the location and identity of each person participating in the synchronous collaboration. These new kind of immersive environments are in contrast to supporting collaboration with access to shared documents as in Wikipedia, Groupboard, Google docs. The shared document approach may support asynchronous collaboration only, such as Wikipedia and Google docs.

In this paper we focus on synchronous collaboration as a more direct comparison to virtual worlds in which the collaborative participants are able to work at the same time on the same shared task. We claim that collaborative behaviour changes when the participants are feeling 'being there' in the collaborative environment. We focus on collaborative design in which the participants are given a design task to co-create a shared external representation of a building design. We compare collaborative sketching environments in which the designers are working together on a document of shared design sketches of the design solution, to a 3D virtual world in which the designers are working together on a shared 3D model of their design solution. We report the results of an experiment using protocol analysis, in which designers' activities (the verbal and visual design communications) are collected and analysed. The significance of this research is to empirically examine the ways in which designers collaborate and design using different digital design environments.

2. STUDYING DESIGN COLLABORATION

This research is concerned with designers' collaborative behaviour while carrying out design tasks using different digital design modes. Designing is already a complex task, when it includes employing digital tools and collaboration with others in a remote location, it becomes even more complicated.

In cognitive research, designing is usually considered as an individual mental process. Early design models endeavoured to metaphorically represent design in abstract, simplified ways and as a linear process (Asimow 1962; Simon 1969). Later studies reported that designing included a set of processes that existed in each of the sequential stages of designing. Those studies pointed out the iterative nature of design processes (Watts 1966; Coyne et al. 1990; Finke et al. 1992; Candy and Edmonds 1994). Gero and McNeill (1998) also reinforced that design thinking consists of a series of distinct events that occupy discrete and measurable periods of time.

According to Cross (2007) designing is not a normal problem-solving activity. However, it involves 'finding' appropriate problems, as well as 'solving' them. Designing includes substantial activity in problem structuring and formulating, rather than simply accepting the 'problem as given'. Therefore design problems are usually acknowledged as wicked, that is, ill-defined and ill-structured (Rittel and Webber 1984). This means that more than one solution is possible, depending on how the design problem is framed and reframed. Thus, design problem solving requires different kinds of thinking to reach the solution, which would also vary for different designers.

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. In general, collaborative design studies assume that the participants are in geographically distant locations working over IT (information and communication) technology. Common issues in these studies involve; (1) investigating participant's communication via different communication channels, (2) analysing the components of collective thinking and team behaviour, (3) analysing social behaviours such as sense of community or team, (4) level of open participation and (5) level of participants' awareness in the computer media (Gül, 2009a). Although these studies have led to important advances in the enabling technologies that are required to support the changes in the design practice, we know very little about the role and the impact of these technologies on the design collaboration.

This article fills a gap in the literature by studying collaborative design activity so that it may be better understood. In addition, this understanding could be employed to improve the efficiency of the collaborative design technology. In particular, this article presents a comparison study that examines a pair of architects' behaviour in a co-design situation over the technology as they solve a conceptual design problem. This study characterises how two designers sketch and model together and how their interactions with the design representation changed in different design environments.

2.1 Collaborative Design Communication

Collaborative designing is defined as a process that involves communication and working together in order to jointly establish design goals, search through design problem spaces, determine design constraints and construct a design solution (Seitamaa-Hakkarainen et al. 2000). Researchers (Kvan et al.1997; Gül, 2009a) pointed out that as collaborators come together in design, the nature of their activity does not change, since collaborative design still requires a designer to attend to design as the individual tasks, as well as collaborating. In a collaboration context, Kvan et al. (1997) pointed out that collaborative design consists of parallel expert actions, each of short duration, bracketed by joint activity of negotiation and evaluation. In this model, designers work separately to solve the problem and come together for meta-planning, negotiation and evaluation as shown in Figure 1. This is a process of identifying the approach of collaboration (who is doing what in 'meta-planning'), identifying key problems ('problem analysis') and proposing (generating new ideas in 'negotiate') and evaluating design alternatives.

With regard to studies on collaborative design (Gül, 2009b; Kvan 2000) in this paper, we will demonstrate the impact of the different design environments on Kvan et al.'s (1997) cognitive model of design collaboration. For demonstrating the impact of the design representations on the cognitive model, we consider employing and coding the verbal and visual design protocols of two designers in a collaborative design context.

2.2 The Nature of Design Representations

Representation is an entity used to represent something else (Hesse, 1966). In design, designers normally use suitable means to mentally create design concepts, apply communication channels to express their design concepts and turn the concepts into external visible artefacts so that designers and other viewers can visualize the design in progress (Chan, 2011). Thus, designers rely on external design representations in several overlapping ways, that is, through at variety of types of sketches, physical and digital models, diagrams, graphs and notations.

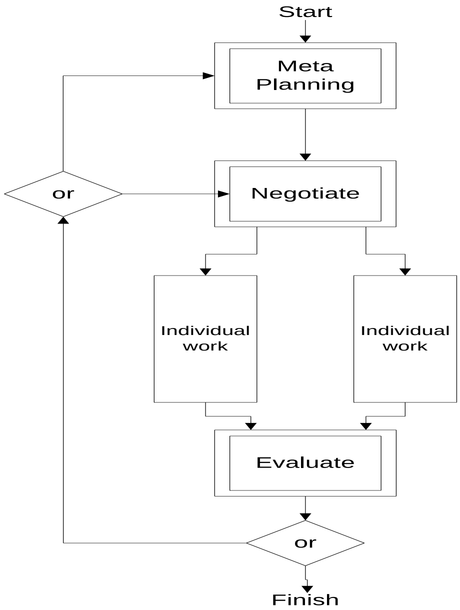

FIG. 1: A cognitive model of collaborative design

An extensive review of literature shows that external design representations have many functions: First, they act as memory aids, for both short-term working memory and long-term working memory. They decrease working memory load by offering external tokens for the objects that must otherwise be kept in mind and free working memory to perform mental calculations on the objects, instead of both keeping objects in mind and operating on them. (Goldschmidt, 1994; Suwa and Tversky, 2002). Second, external representations carry information that can be directly perceived and utilised without being interpreted and explicitly formulated, such as visuo-spatial and metaphoric calculation, inference and insight (Cox and Brna, 1995; Larkin and Simon, 1997; Suwa and Tversky, 1996). Next, they function as an aid in organising cognitive activity (Chandrasekaran et al., 1993). In addition to supporting the design activities of iteration and problem formulation, external representations support the communication of design decisions (see Cardella et al., 2006; Römer et al., 2001) with clients, team members, and other related parties.

In the collaborative design context, the meaning of the design representations conveyed in different design settings has great importance. There are five categories of design representations that have been commonly used (Chan 2011): pencil-and-paper, handmade physical models, graphic/modelling software, film and video, and Virtual Reality (VR). Those design media are tools which require unique mental operations, procedures, techniques, and representations to convert concepts into forms, which are parts of design cognition, defined as the human abilities or intelligences to organize design information and problem structure for creating man-made artefacts (Chan 2011).

Representations that have a significant role as communicative resources are the objects of interaction (Robertson, 1996). When design thoughts are externalised through objects, each object contains properties of future interpretations that designers can negotiate during further developments to the design. Objects that can be pointed to talked about or sketched on (Perrya and Sanderson, 1998) play an important role both in one's conversation with her/himself and with others. Most importantly, these external representations become the ground on which conflicts and collaboration take place. Arias et al. (2000) put forward that the externalisations were especially important for collaborative design, because externalisations in collaborative design: (1) create a record of the mental efforts, one that is "outside us" rather than vaguely in memory, (2) represent artefacts that can talk back to us (Schön and Wiggins, 1992), and (3) form the basis for critique and negotiation (Arias et al., 2000).

Cohen (1944) pointed out that "[…] anything acquires meaning if it is connected with or indicates, or refers to something beyond itself, so that its full nature points to and is revealed in that connection" (p. 47) (as cited in Kalay, 2001). He argued that the properties of meaning have a three-way relationship between: (1) the object (the "stimulus"), (2) its referent (the "consequent"), and (3) the conscious observer. Thus the meaning could be "referential" and "inferential": The referential meaning refers to objects that acquire meaning by association with other objects and the inferential meaning refers to objects that permit different observers to interpret the reference differently. In a collaborative design context, the referential meaning of design objects could be externalised through verbal exchanges, but the inferential meaning seems to be related to an individual's visual reasoning and perception. In their studies on visual reasoning and perception, researchers have investigated what designers perceive in their design representations and how their external design representations facilitate design (Gül, 2008; Suwa and Tversky, 1997; Suwa et al., 2001). Suwa et al. (2000) pointed out that the acts of attending to visuo-spatial features in sketches contributed "unexpected discoveries". Suwa et al. (2000) called this process the "detection of unintended relations and features". The generation of new ideas may occur immediately after unintended visuo-spatial features in external representation, and the re-generation of ideas and unintended visuo-spatial discoveries comprise the core cognitive processes of designers (Suwa et al., 2000; Suwa and Tversky, 2002). In addition, reasoning from visuo-spatial features of the external design representation requires functional inferences related to the behaviours of entities in problem-solving tasks (Carroll et al., 1980). Tversky (2005b) pointed out that making functional inferences requires linking perceptual information to conceptual information by using additional knowledge.

Our interest is not in the mental reasoning of the design representation, which might not be captured during the design dialogue, but rather in the referential and inferential meanings of the design representations that are articulated verbally and visually during the collaborative design task. In this paper, in terms of the properties of the design representations for conveying meaning and facilitating design collaboration, we particularly examine two types of design representations: sketches and models.

2.2.1 Sketches

According to studies in the field of psychology, a sketch can serve to facilitate collaboration (Heiser et al., 2004): (1) it serves as a shared focus of attention, insuring that both partners are considering the same thing, (2) it simplifies communication by allowing gestures to convey spatial temporal information, and (3) it encourages interactivity between the participants, enhancing their evaluation and enjoyment of the collaboration.

In design collaboration, the use of quick-drawn sketches in support of group discussions may provide for a more efficient design process by providing a shared visual context (Remko, 2002). Thus, the act of sketching itself is regarded as important in team design activities, in conjunction with having the function of communicating and discussing ideas through sketches (Remko, 2002). In another study in the design collaboration context, Lugt (2005) pointed out that (1) sketches supported a re-interpretive cycle in the individual thinking process, and (2) sketches enhanced access to earlier ideas. The same study also found no evidence that sketches supported re-interpretation of each other's ideas in-group activities.

2.2.2 Models

Models play a vital role in the practice of architecture (Williams, 2002). Within the process of architectural design, models are suggested as an essential tool in the realisation of habitable built form. Having large varieties of components as well as static and dynamic relationships between the parts and the whole, the design solutions tend to be complex in nature (Peng, 1994). Therefore, for complex problems of visual design, alternative techniques have been developed to convey and manage the complexities of the design problem. Model making is one of these alternative techniques. Making the model represents the concretisation of ideas, by getting as close as possible to the actual construction of a design idea. Investigating the exterior and interior form, structure, colour, surface and lighting would become easy. In addition, models can help with the creative process of visualising three-dimensional space directly in the round as well as by functioning to help with complex visual relationships, so the models outperform drawings (Porter and Neale, 2000).

Computer technology has been increasing its expressive and geometric power to enable the design process in which a digital model can be used throughout the whole process for realising the design (Achten and Joosen, 2003). In this new design processes, the digital models are considered as new design representations that have a consistency and long life-span which does not require continues reconstruction, in contrast to sketches and physical models, which involve considerable redrawing, tracing and scale-model-making (Achten and Joosen, 2003).

2.3 Studying Visuo-Spatial Features And Affordances Of 'Being There'

In a collaborative design context, understanding of the reasoning on the external design representation, which has related with 'the properties of the representation' and 'the feeling of being there' is vital. First, 'the properties of the representation' includes the designers' reasoning on the external design representations that is to capture "visuo-spatial properties of the world" (Tversky 2005a). This includes visual and spatial information. The spatial information includes the properties that are "close or above or below" in the world preserving those relations of the representations. The visual information includes static properties of objects, such as shapes, textures, colours, or relationship between objects and reference frames, such as distance and direction (Tversky 2005a).

Another area of the study, presence, is defined as 'psychological state or subjective perception in which even though part or all an individual's current experience is generated by and /or all filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience' (International Society for Presence Research 2000).

In a collaborative context, social presence refers to the feeling of being together with a virtual or remotely located communication partner (Riva et al. 2003). Providing sense of presence is considered important in virtual environments applications. In virtual environments the concept of presence which 'is extremely subjective and behavioural' (Steuer, 1992) has a ubiquitous component of 'the sense of being in a place'. Clearly, the sense of 'being there' in computer-mediated platforms is associated with various factors that are perception, content, cognitive processes and affordability. Witmer and Singer (1998) state that presence is brought about by focusing the attention on a 'meaningful coherent set of stimuli'.

The concept of presence is relevant with the interaction with the surrounding space. Tversky (2005b) defined four types of space in which human activities occur:

- The space of the body;
- The space around the body;
- The space of navigation; and
- The space of external representations.

Each of the above activities 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). Digital design environments have the potential to provide the above mentioned sense of spaces which may have different kinds of impact on affordances of 'being there'.

The 3D virtual worlds are intended to create "the illusion of participation in a synthetic environment rather than external observation of such an environment" (Gigante 1993). Depending on the external devices used, the 3D virtual environments could enable people to become 'immersed in the experience' of interacting with the external representations (Kalawsky 1993). 'The sense of immersion' is defined as the level of fidelity that virtual environments provide to the user's senses (Narayan et al. 2005), which could be enhanced with the use of human-shape characters (avatars) (Hoon et al. 2003). In our experiments, the virtual world is a desktop system wherein the designer is represented by the avatar. The avatar can fly, walk, sit and touch the objects, thus this real-life-like behaviour of the avatar creates an illusion of immersion.

3. COLLABORATIVE SKETCHING VS 3D MODELLING IN VIRTUAL WORLDS

In order to understand the impact of virtual worlds on synchronous collaborative behaviour, we interpret that the research should consist of the following issues: how collaborative design behaviour changes; how the interaction with the design artefact changes; how their perception on the spatial arrangements changes; and how their reasoning on the visuo-spatial features of design changes. In this paper, we analyse two expert designers' dialogues while they are collaborating over several design environments using protocol analysis. This phenomenon of understanding the effect of digital design representations on the synchronous collaborative design behaviour has not been studied in the field.

This section describes two synchronous collaborative environments that are being compared: Groupboard (remote sketching environment) and Active Worlds (3D virtual world), where the designers interact with the external design representation and with each other. A series of experiments is conducted to investigate the impact of digital design representations on design collaboration behaviour. We have reported the results of a broader study in terms of the impact of remote collaboration on the co-creation of an external representation in (Gül 2009a). In this paper, we revisit the protocol data with a focus on understanding the effect of digital design representation on synchronous collaborative design behaviour. Here we will look at the data collected while the designers were using a remote collaborative sketching environment and a 3D virtual world.

3.1 Experiment Setups

To highlight the changes in collaborative design behaviour, we compare designers in the following two settings: remote sketching (RS), and 3D virtual world (3D). The designers were located in the same room with a panel between them to simulate high bandwidth audio communication. The same designers were given different tasks of similar complexity in each setting. During the comparison study, their actions and communication were recorded in the Digital Video Recorder (DVR) system, as shown in Figure 2.

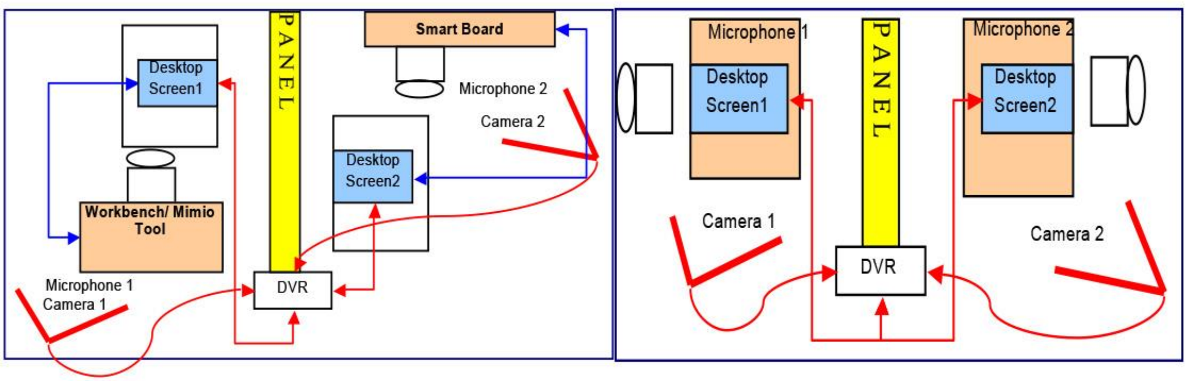

FIG. 2: Equipment setup for the comparison study (a) RS session, (b)3D session

In the remote sketching (RS) session, the study participants used a shared whiteboard application (Groupboard) and digital pen interfaces (Mimio and SmartBoard), as illustrated in Figure 2a. Mimio and SmartBoard were digital touch systems allowing the designers to use the digital pen as a mouse and to write in digital ink on the screen. In the RS session, the architects are asked to design a contemporary library, which includes a foyer, open access bookshelves, reading area, loan desk, offices, audio-visual library, a small theatrette and services.

In the 3D virtual world (3D) session, the architects worked together in Active Worlds using a typical desktop system with mouse, keyboard and a monitor, as shown in Figure 2b. In the 3D session, they are asked to design a fine arts and dance school, which includes studio spaces, offices, foyer, amenities, services and café.

3.2 Design Modes

Groupboard (GB) is a set of multi-user java applets including a shared-whiteboard, text-based and video-based communications channels, drawing and manipulations tools and file management tools (Figure 3). Our designers used digital-ink based tangible interfaces during the remote sketching: (1) the Mimio Capture[i] tool which is set up on a large horizontal projection table, and (2) the Smart Board[ii] which has a large vertical liquid crystal display (LCD) panel. In both systems, the designers used the digital pen as a mouse and wrote in digital ink on the screen. GB offers a shared design representation, which provides a basis for the collaborative design activities. In GB, users could draw/delete/edit concurrently the drawing or a part of the drawing. The ownership of the elements is not a problem. However, the screen requires an update to show the current drawing and a delay on updating the current situation of the floor plans can occur.

Over the years, a variety of 3D virtual worlds such as Adobe Atmosphere[iii] , Blaxxun[iv], Virtools[v] and Virtual Worlds[vi] have been tested and applied in design studies. AW was chosen because it supports a distinctive design method for 3D virtual worlds. AW also possesses an active online community, which can provide useful resources for inhabiting, studying and designing virtual worlds. AW supports the so-called library-based design method. Typically, a library-based design comprises a set of objects whose forms are pre-defined outside the world and provided by the object library of the design platform. Modifying the forms requires object library updates. As a result, library-based designs can share the uniform “AW look”, due to the repetitive use of standard library objects. A set of design elements (walls, slabs, space objects and columns) and navigation signs are provided at the entrance of the site (Figure 4).

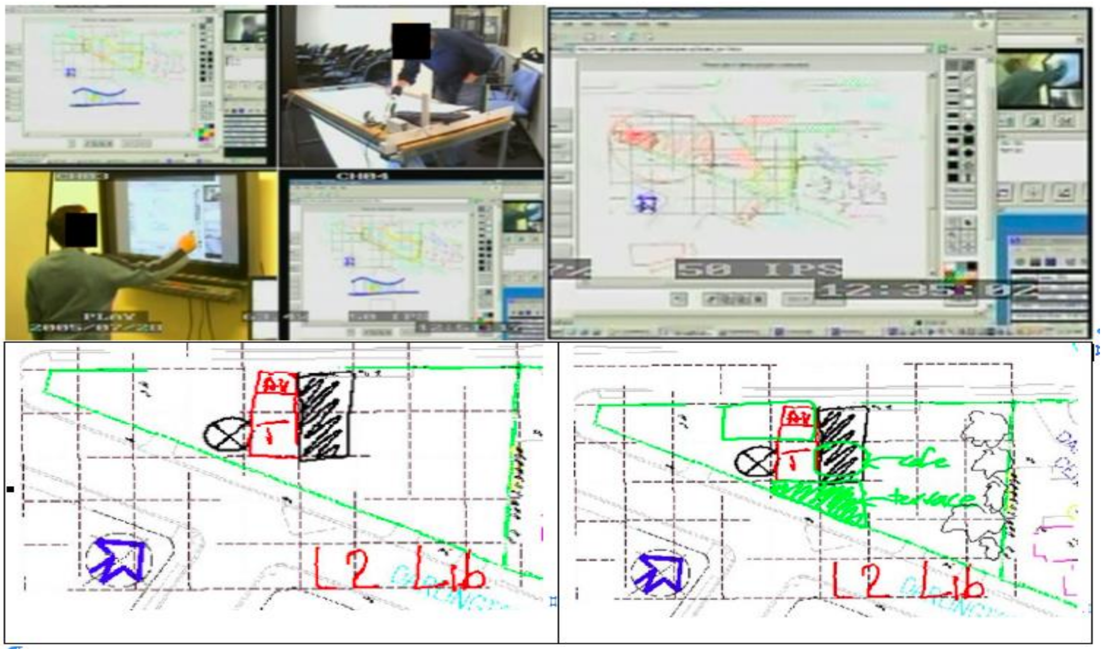

FIG. 3: Remote Sketching session: Designers using Mimio and SmartBoard (left) and the interface of Groupboard (right)

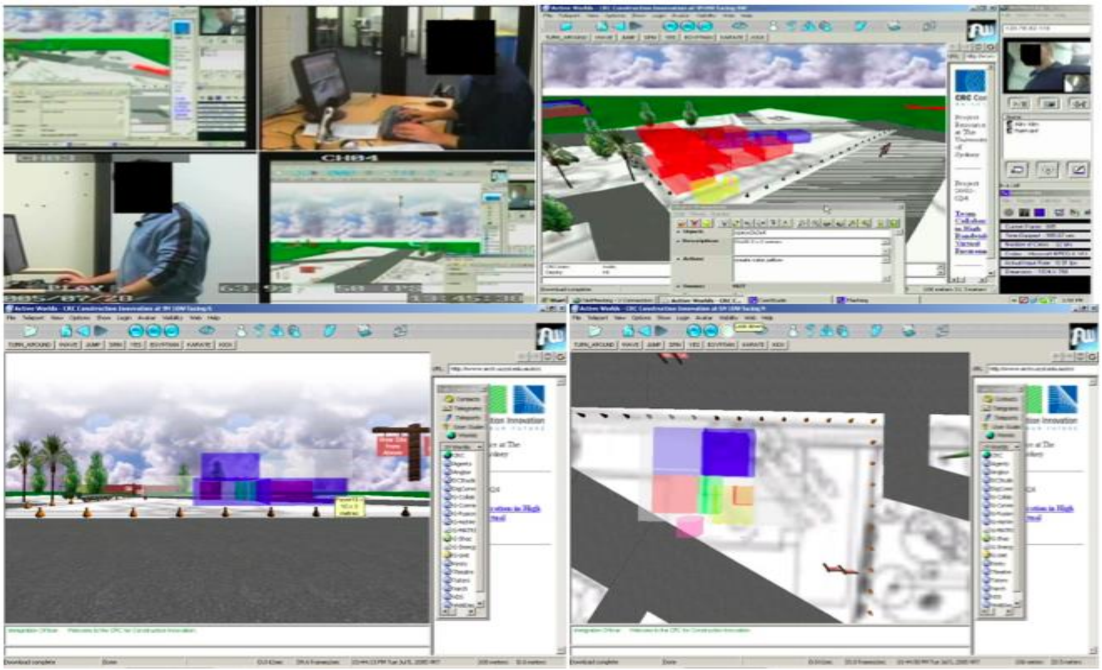

FIG. 4: 3D modeling in Active Worlds, the interface and study participants and several views of the design mass

4. PROTOCOL STUDY

One way to study collaborative behaviour is to perform a protocol study in which the designers are given a design task, verbal and visual data is collected while they perform the task, and the protocol data is analysed using a coding scheme that measures the characteristics being studied.

4.1 Protocol Analysis in Collaborative Design Studies

Protocol analysis that allows the characterisation of the processes in designing has been used in different design disciplines, such as architectural design, interior design, industrial design, mechanical engineering and software design. Early studies focused on a protocol's verbal aspect (Ericsson and Simon 1984). In addition, early design studies were usually single-subject, think-aloud protocol studies that required the externalisation of the thoughts during designing. Later studies acknowledged the importance of the design drawings that are associated with the design thinking which can be interpreted through verbal descriptions (Suwa et al. 1998; Akin 1996).

In the late 1980s, a rapid change occurred in the protocol studies by extending single-subject design activity to the team's design activity (Schön 1984; Scrivener et al. 1992; Cross et al. 1996; Kvan et al. 1997; Gabriel and Maher 1999). Cross et al. (1996) pointed out that a team's design protocols resembled the "think aloud" method, since a joint task seemed to provide data indicative of the cognitive abilities that were being undertaken by the team members. Consequently investigating the team's design protocol was not substantially different from investigating single-subjects' design thoughts.

4.2 Coding Scheme

Purcell et al. (1996) presented three approaches for developing the structure of a coding scheme: theory based, externally derived and data generated structures. This study uses the latter approaches: externally derived and data generated. The expected result of the study is that the different design representations will change the ways in which the designers collaborate and design. A collaborative design process coding scheme that classifies the design protocol (verbal) into two levels is developed: (1) the collaboration process and (2) the design representation. The hierarchy of the coding scheme is shown in Figure 5. The collaboration process category captures the discussions between designers in terms of how the design solutions are developed and generated and how the ideas are communicated. This category is further divided into sub-categories, as illustrated in Figure 5. The design representation category has several sub-categories such as agent's actions, representation mode, realization actions and realization processes (see, Gül, 2007). In this paper, we present the results of the collaborative design process, the design semantics and the perceptual focus category, as shown in Figure 5. The visual and verbal design protocols are employed to investigate the relationships between the design objects and the avatar in the virtual environments.

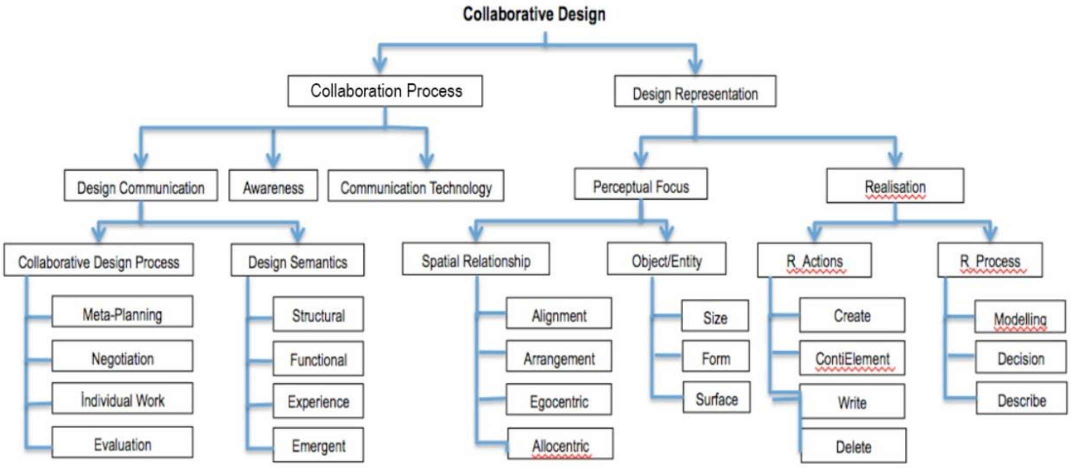

FIG.5: A hierarchical tree of the coding scheme

4.2.1 Collaborative Design Process

The first sub-category, collaborative design process, is derived from Kvan et al.'s (1997) cognitive model of collaborative design. The category has four codes: meta-planning, negotiation, individual design work, and evaluation, as shown in Table 1. In Kvan et al.'s (1997) cognitive model, meta-planning, negotiation, and evaluation are considered as cooperative steps whereas individual design work is not.

TABLE 1: The design collaboration process

Design collaboration process	DESCRIPTIONS	Verbal
Meta-planning	Coordinating the activities of the collaborators, task allocations, management of the process	
Negotiate	Negotiation regarding specific aspects of the design problem/joint interactive decision-making	
Individual design work	Working individually on the design problem	
Evaluation	Evaluate and explore design idea	

4.2.2 Design Semantics

The second sub-category, design semantics, includes four actions that are related to mapping or indexing a meaning to design representations: structural, functional, emergent properties and past experience/knowledge, as shown in Table 2. The first two codes are adapted from Gero and Rosenman's (1990) framework: function-structure. Those codes capture discussions held between participants related to the functional arrangement of the spaces and the structural issues of the design solution. The emergent property code that is adapted from Suwa et al.'s (2000) information categories, captures whether designers see new shapes, forms, properties or ideas from the existing design representation. The past experience/knowledge code looks at the discussions held between participants related to their past experience or their knowledge, which could be adaptable to new design solution.

TABLE 2: The design semantic actions

Design Semantics	DESCRIPTIONS	Verbal
Functional thoughts	Engage with the functional aspects of elements	
Structural thoughts	Engage with the structural aspects of elements	
Emergent property	Discover new features of elements	
Past experience/ knowledge	Discussion related to the past experience or knowledge	

4.2.3 Perceptual Focus

The third sub-category, perceptual focus, has two codes: the object and the spatial relationship, which are also sub-divided, as shown in Table 3. In this category, based on Tversky's (2005a) view on the visuo-spatial properties of the world, the visual and the verbal design protocols are investigated to determine the codes: 'object' and 'spatial relationships'. The 'object' is coded when designers discuss/engage with the visual features of the design solution. The 'spatial relationship' is coded when designers discuss/engage about the spatial relationships of the objects. The object and the spatial relationships actions are also divided into the sub-codes to capture the detailed information on the designers' perceptual focus on the design representation, as shown in Table 3.

TABLE 3: The perceptual focus actions

Perceptual Focus	DESCRIPTIONS	Verbal-Visual
Object		
Size	Discuss and engage with size and dimensions of the objects/entities	
Geometry/Form	Discuss and engage with geometry and form of the objects/entities	
Surface features	Discuss and engage with colour, texture and material of the objects/entities	
Spatial Relationships		
Alignment	Discuss and engage with the spatial location and position of objects/entities	
Arrangements	Discuss and engage with grouping of objects/entities	
Egocentric	Discuss and engage with local relations based on one's current location (being left/ right or up/down)	
Allocentric	Discuss and engage with global relations based on environmental objects (a neighbouring building, the sun, a river, a road, north, south)	

4.3 Segmentation

During segmentation, the protocol data is divided into smaller units. The data consists of a continuous stream of video and audio that has two sources, designer 1 (Greg) and designer 2 (Lee). In order to investigate the verbal and visual design protocols of each of the designers in the collaborative design context, we first segmented the protocols twice for each designer using the utterance-based segmentation method as used in (Gabriel 2000; Maher et al. 2005). Then, in order to separate the utterances into meaningful units, which can be coded under a specific category relating to the design processes and actions, we segmented each utterance further using the actions-and-intentions segmentation method used in (McNeil et al. 1998).

The segments are individually coded by two coders and a final coding is achieved using a process of arbitration, adapting the Delphi method (see Mc Neill 1999 for more details). The coders select codes for each segment by watching the audio-video data and reading the transcription of segments in chronological order. In this study, the INTERACT software[vii] is used to facilitate the segmentation and coding of the video sessions.

4.4 Coding Process

Following the transcription of the utterances, segmentation was done by one of the coders. Then, the protocols are coded individually by two coders and a final protocol is achieved using a process of arbitration. By adapting the Delphi method (see Mc Neill, 1999 for more details), the coders, who are the author and an expert architect, make a first pass of the coding, separately. The coders individually decide on the codes by watching the audio-video data and reading the transcription of segments in the numerical order, based on her/his understanding of the content of the segments and the coding scheme using INTERACT software.

In the experiments, two designers collaborated in each session, consequently the resultant coding list contains two versions with intersecting events representing each designer's behavioural patterns. In the collaborative design activities, designers usually have parallel actions. For example, they may sketch/model while they are talking. Because of this complexity, each design session was coded separately for reflecting each designer's actions.

Each coded list is specific to one participant's actions and verbalisations. After both coders finished the individual coding, they combined their results in a joint arbitration process in order to achieve the final protocol. The coders consulted the transcripts and referred to the audio-video data when it was necessary to clarify the designers' actions and intentions as well as to reach an agreement on each other's protocol. When there was a disagreement, each coder offered reasons for her/his results and by a consensus approach the arbitrated results were achieved. The reliability of the coding process for the study was measured by calculating the Kappa values between the two coders.

4.5 Reliability Of The Coding Process

To compare the results of the two separated coded data, the Cohen's Kappa (Cohen, 1960) analysis is used. Cohen's Kappa coefficient is a statistical measure of the "inter-rater" agreement that gives a score of how much homogeneity, or consensus, there is in the ratings given by coders. The Kappa value has a range from 0–1, with larger values indicating better reliability. Landis and Koch (1977; as cited in McBride, 2005) proposed this scale to describe the degree of concordance: 0.21-0.40, "fair"; 0.41-0.60, "moderate"; 0.61-0.80, "substantial''; 0.81-1.00, "almost perfect". In this paper, generally a Kappa >0.65 is considered satisfactory.

Kappa values between the three coding phases (first coder run, second coder run and the arbitration session) in all design sessions are shown in Table 4. We calculated the Kappa values for each coding category separately. The last row shows the average Kappa for each coding category and the last column shows the average Kappa for each session, in Table 4. The values are greater than 0.65, which means the reliability of the coding process is acceptable. We observe that the reliability of the representation mode is high. The reason for this might be that these actions are determined by inspecting what happens on the screens. In the other action categories, the coders needed to look at the screen and read the transcriptions; determine from the content and actions whether the actions or intentions refer to any codes in the list.

TABLE 4: Kappa values for the three coding phases the RS and the 3D sessions

	Kappa Values Between					
	Collaboration Process			Perceptual Focus		
	1and2	1andA	2andA	1and2	1andA	2andA
RS Session	0.69	0.66	0.67	0.91	0.93	0.92
3D Session	0.71	0.74	0.73	0.87	0.92	0.89
Average	0.70	0.70	0.70	0.89	0.93	0.91

Note: 1and2: First coder's coding and second coder's coding; 1andA: First coder's coding and arbitrated coding; 2andA: Second coder's coding and arbitrated coding.

5. ANALYSIS OF COLLABORATIVE DESIGN

The encoded protocols are compared to understand qualitative differences between the design representations. Encoded protocols represent the context of collaborative designing, how designers collaborate and communicate, and interact with the design representation. In this section, the duration percentages of each action category are examined to measure the similarities and differences of designers' behaviour in each design session. To examine the changes affected by the design environments, the patterns of designers' behaviour are also explored visually through the timeline graphs.

5.1 Overview Of The Coded Data

The average duration percentages of the two architects collaborating in two design modes are presented in Table 5. The duration of each category is divided by the total elapsed time for each design sessions (30 minutes). Then the duration percentages for each category are determined. The duration percentages of design representation categories (the perceptual focus, the realization process and the realization actions) are higher in the 3D session, and the duration percentages of the collaborative design processes categories (overall communication, the collaborative design process and the design semantic) are higher in the RS session. The overall communication includes the design-related utterances as well as the awareness and the technology-related discussions. This finding suggests that the designers communicated less in the 3D session.

TABLE 5: The duration percentages of the categories

Duration %	**Overall Communication**	**Collaborative Design Pro.**	**Design Semantic**	**Perceptual Focus**	**Realisation Process**	**Realisation Actions**
RS	97%	73%	80%	53%	67%	33%
3D	93%	67%	59%	81%	83%	49%

5.1.1 What Did They Talk About?

The duration percentages of the first level of the collaborative design process actions are shown in Figure 6a, indicating the communication content during sessions. The durations are divided by the total time elapsed in each session, where the duration percentages are obtained for each code. Duration of actions based on each designer is also shown in Figure 6b. Not surprisingly, they talked about designing most of the time in the entire sessions, as illustrated in Figure 6. When the designers moved to the 3D virtual world, the communication content was still mainly about designing (design Com), followed by the awareness and communication about software features (Comm Tech). The discussions relating to the software features (Comm Tech) were higher in Groupboard, as shown in Figure 6. In addition, the awareness code is higher in the Active Worlds, in which the designers discussed the locations and each other's actions, as shown in Figure 6.

In the remote sketching session, it has been observed that the designers have more technology-related dialogue and less awareness-related dialogue. The reasons for that might be: (1) the complexity of the application's interface and (2) the shared nature of the design representation. First, the drawing activities in the remote sketching, which requires constant drawing, loading, choosing the colour and the thickness of the pen, seems to require certain knowledge of and skills in using Groupboard. Second, in Groupboard, the design representation is a shared representation that provides a shared workspace, ensuring awareness of each designer's drawing actions.

In the 3D virtual world, on the other hand, the analysis shows that the duration percentages of the technology-related discussions are less, but the duration percentage of the awareness action is higher. This finding could suggest that maintaining the awareness requires constant communication about the actions and locations of each designer in the 3D virtual world. Active Worlds allows individuals to move freely around the 3D workspace while still providing information about the shared design representation and the position of the others (via the presence of the avatars) but the technique of manipulating the design objects does not support workspace awareness. In Active Worlds, the designers are not able to see others' modelling actions, unless the command is finalised. Therefore maintaining collaboration and monitoring each other's actions becomes an issue

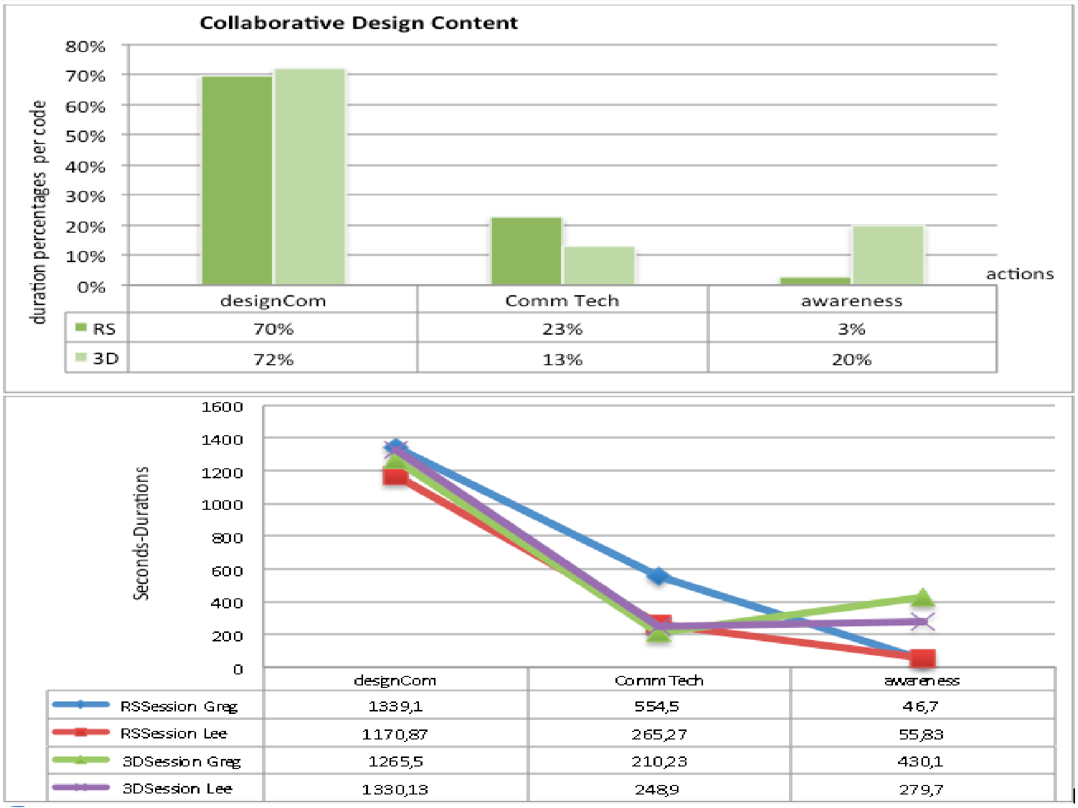

FIG. 6: a-The duration percentages of communication content actions (top), b-Durations of communication context actions of each designer.

5.1.2 How Did The Attention Shift During The Design Collaboration?

The attention changes/shifts are examined by an analysis of the segment durations in each of the design sessions, as shown in Table 6. Since we segmented the continuous stream of data according to a change in the design protocols, the numbers of segments in each session provide us with information about how frequently the changes/shifts occurred. Table 6 shows the descriptive statistics of the segment durations for each designer (Greg and Lee). Table 6 shows that Greg's attention shifted quickly in the RS study (M11.38) and when he moved to the 3D mode, the time spent on each action increased, but the number of segments decreased in the 3D mode. On the other hand, Lee's attention shifts show a drop in the 3D mode (M12.62) as shown in Table 6. We also observed that Lee has the higher segment numbers (170) in the 3D session, compared to the RS study. The differences between the two designers in each design session in terms of the durations of segments are tested. An independent groups t-test revealed that the designers' attention shifts differed in the RS mode ($t[350] = 7.395$, $p = 0.007$) but not in the 3D mode ($t[333] = 0.269$, $p = 0.604$). This shows that the designers had consistent attention shifts in the 3D mode, however, their attention shifts varied in the RS session.

In the remote sketching session (RS) the average mean (M) duration of segments is the shortest (M12.2 second) and the average number of segment is the highest (176 count). On the other hand, the average segment durations (M12.84 seconds) increased and the average number of segments (168 count) decreased in the 3D virtual world session (3D), as shown in Table 6. The longest segment durations (52 second) are observed in the Active Worlds, when the designers spent time elaborating on the design model. The segment durations for all sessions are positively skewed, as illustrated in Table 6.

TABLE 6: Statistics on the duration of segments

Duration second	RS		3D		Average	
	Greg	Lee	Greg	Lee	RS	3D
Mean	11.38	13.03	13.06	12.62	12.2	12.84
Standard Deviations	5.42	5.96	7.57	7.95	5.73	7.76
Kurtosis	1.549	0.95	4.263	11.338	1.25	8.00
Skewness	0.96	1.00	1.73	2.71	0.99	2.25
Minimum	1.8	2.6	3	1.9	2.2	2.45
Maximum	31.1	31.1	47.5	56.5	31.10	52
Count	187	165	165	170	176	168

The distribution of segment durations along the segment numbers in the design sessions is shown in Figure 7. Similar to what we was shown in Table 6, the graph demonstrates that the segment durations are longer in the virtual world, and shorter in the remote sketching session. This result shows that the designers experienced more attention shifts in Groupboard (less time and more segments), and they had less and longer attention shifts in the Active Worlds. This result suggests that in sketching, conceptual designing and representing the design ideas took less time, and in 3D virtual worlds it took longer time for each design intention to be completed. We could interpret that this consistent data showing longer segment duration in virtual world is due to: (1) the virtual world slows the designers down because the virtual worlds require more cognitive work and/or (2) the designers pursue each action in more detail in the virtual worlds.

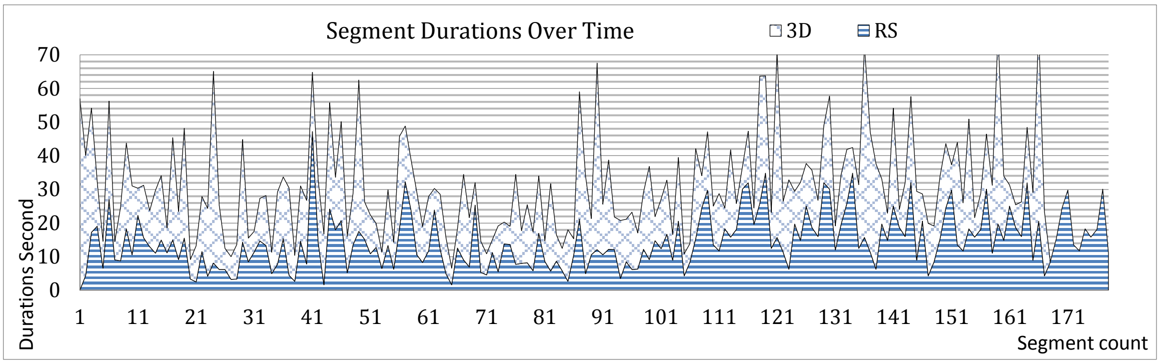

FIG. 7: Distribution of the segment durations over time

5.2 What Did Change In Designer's Behavior?

The two designers' collaborative cognitive behaviour is investigated based on the following categories: the collaborative design process, the design semantics and the perceptual focus actions.

5.2.1 Collaborative Design Process Actions

Figure 8 shows the average durations of the collaborative design process actions over time in all design sessions. In the remote sketching (RS), the duration percentages of the 'negotiate' is higher. In the 3D session (3D), there is an increase in the duration percentages of the 'meta-planning' and the 'individual work' actions, as shown in Figure 8. In Groupboard the 'individual work' action did not take place, representing only 0.2%. However, in the Active Worlds, this action is observed (14.4%), as shown in Figure 8. The cognitive model of design collaboration (based on Kvan, 1997) agrees very well with the results, except that there is very little 'individual work' in the sketching session. Having a shared representation and a shared view might have an impact on this result.

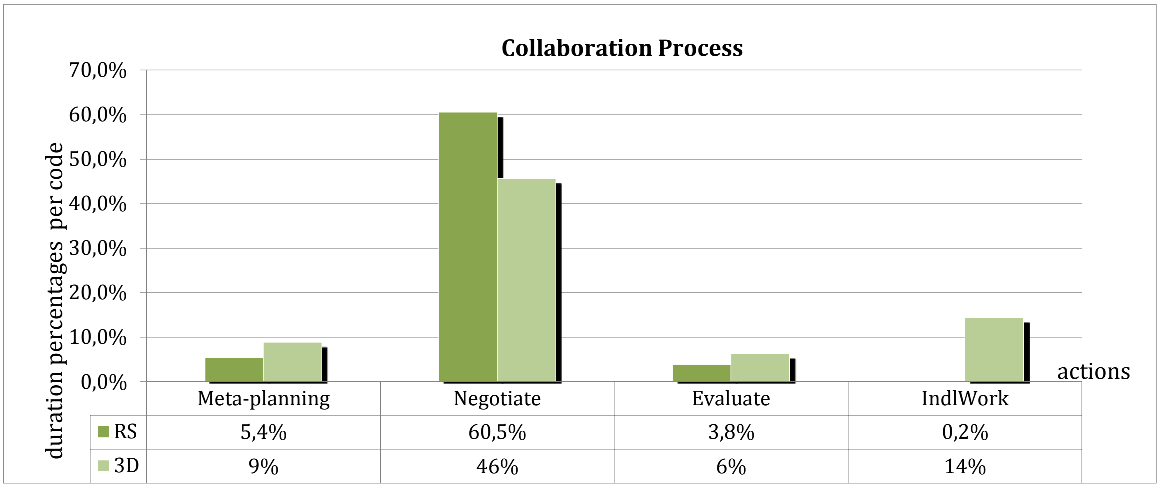

FIG. 8: The duration percentages of Collaborative Design Process actions

The collaborative design process actions are shown along the timeline of the sessions in Figure 9. Each horizontal bar shows the beginning of the sessions, on the left, and the durations of each operation. The numbers 1 (Greg) and 2 (Lee) indicate each designer's actions, which are coded separately. In Groupboard (RS) the designers worked together during the session. In Groupboard the designers spent less time on 'meta-planning', which occurred at the beginning of the session, and spent more time on the 'negotiation' action. In contrast to the RS session, different behaviour patterns are observed in the 3D virtual world session (3D). The most apparent distinction is having the individual work actions in Active Worlds. The designers worked on the separate parts of the design problem and came together for the 'meta-planning', the 'negotiation' and the 'evaluation actions' repeating the pattern many times during the session, as illustrated in Figure 9.

The ability to move around the design model using the avatars, having a different view of the same design representation and some of the modelling features of the Active Worlds might encourage the designers to plan the actions and tasks in advance, then become separated and work on their individual parts of the design model. It is also noted that in Active Worlds, there are more blank spaces shown in the collaboration process actions timeline. The reasons for this might be: (1) the designers did not externalise their thoughts all the time while they were modelling in the Active Worlds, and (2) they might be talking about the software features and/or the locations and actions of each other.

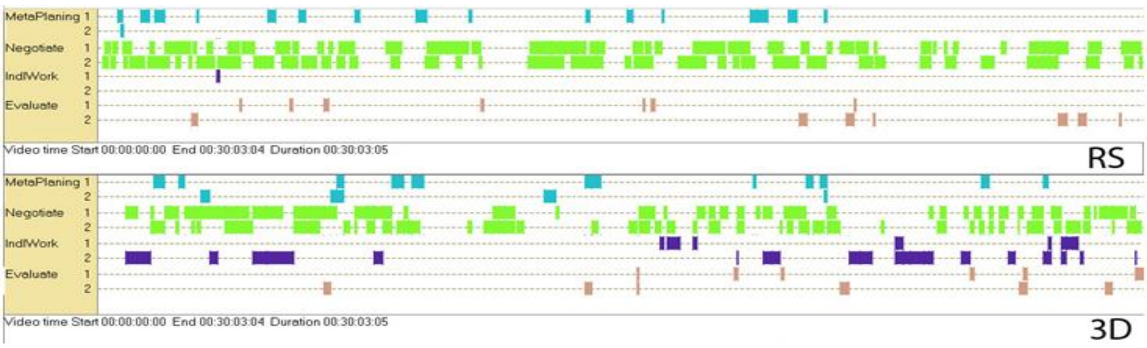

FIG. 9: The collaboration process actions over time

5.2.2 Design Semantic Actions

Figure 10 shows the duration percentages of the design semantic actions of the designers. The graph shows that in the RS session, the designers exhibited more functional action, followed by structural, emergent properties and past experience actions. The bar chart also shows that in the 3D session, the designers used more structural actions, followed by functional, experience and emergent actions, compared to the RS session. The duration percentages of the past experience and the emergent properties actions are low, less than 5% in the design sessions, as shown in Figure 10.

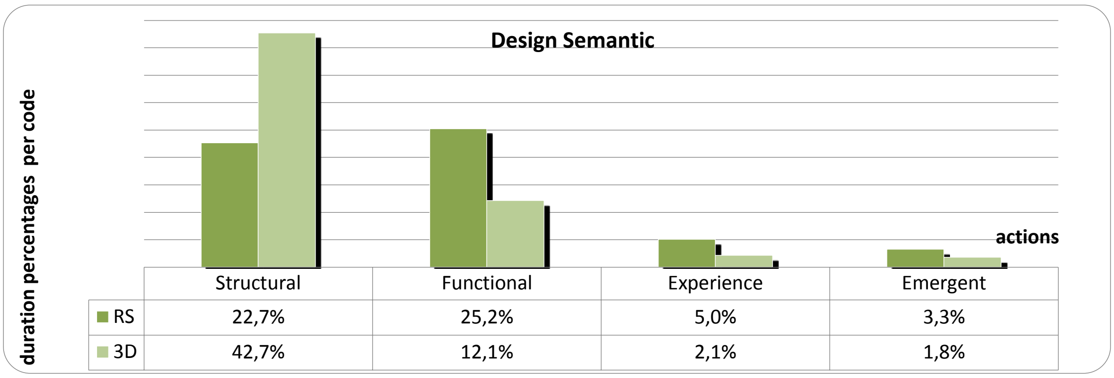

FIG. 10: The duration percentages of the design semantic actions

The design semantic actions are shown along the timeline of the sessions in Figure 11. In the RS session, the designers iterated between the structural and the functional actions during the session, as shown in Figure 11. The experience action occurred during the first half of the session and the emergent action occurred during the second half of the RS session. This happened while the designers were reading the brief and recalling past experiences, reflecting their knowledge of designing. In addition, in the RS session, the designers iterated between the structural and the functional actions during the design session. The 3D session showed different patterns of behaviour when we compared it to the RS session. In the 3D session, the designers exhibited less frequent functional action and more frequent structural action, the latter occurring in larger chunks. Similar to the RS study, the experience action occurred during the first half of the session and the emergent action occurred during the sessions, except that these actions were less frequent in the 3D session.

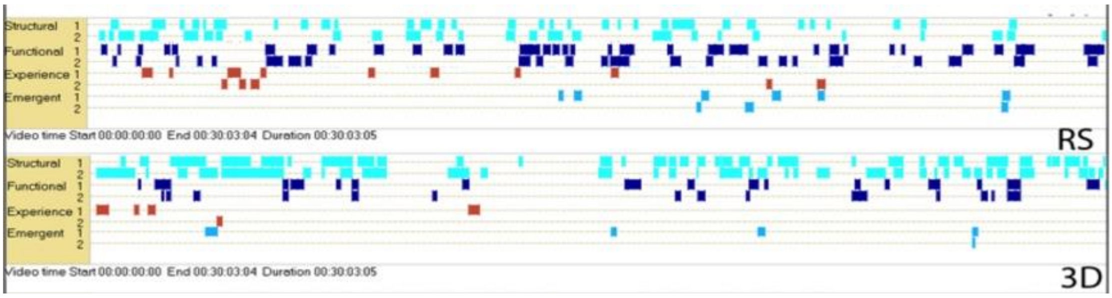

FIG. 11: The design semantic actions over time

5.2.3 Perceptual Focus Actions

Figure 12 shows the duration percentages of the perceptual focus actions of the designers comparing the RS session with the 3D virtual world session. The duration percentage of the object/entity action is higher in the RS session. In the 3D session, there is an increase in the duration percentage of the spatial relationships action, as illustrated in Figure 12. This shows that the designers focused on the visual features of the design solution in Groupboard, and they focused more on the spatial relationships of the design model in Active World.

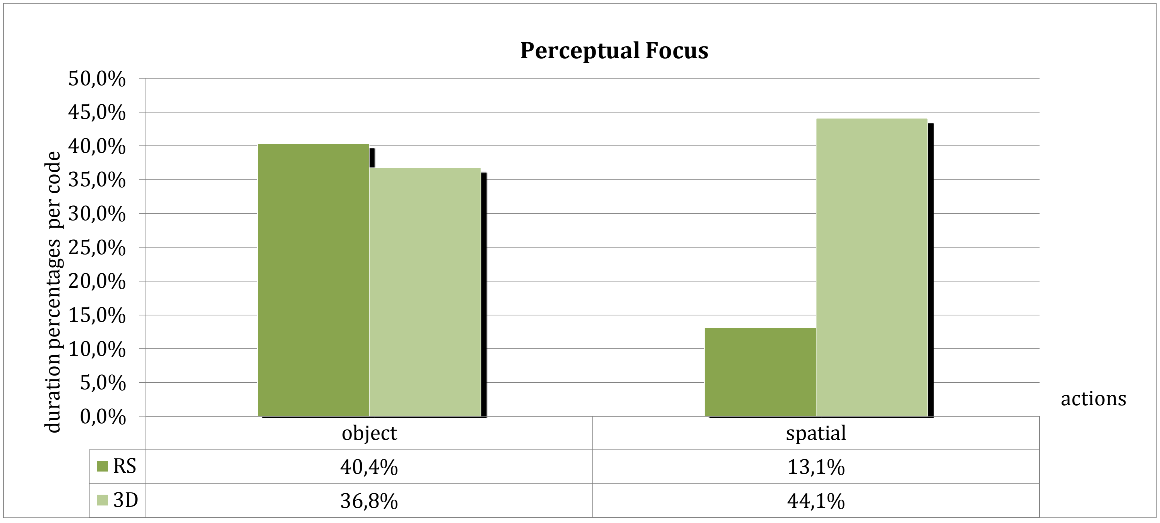

FIG. 12: The duration percentages of the perceptual focus actions

The durations of the object/entity actions are investigated in order to understand what kind of visual features the designers focused on. Table 7 presents a detailed examination of the object/entity actions (visual features) over time in the two design sessions. We observed that the designers focused more on the height and length (size) of the design elements (21.9%), and on the geometry/form of the shapes (form) in the RS session (12.6%) and on texture/colour (surface) in the 3D session (5.5%).

TABLE 7: The durations of the perceptual focus on the object/entity actions

Second - %	RS		3D	
size	788	21.9%	745.	20.7%
form	452.87	12.6%	337.54	9.4%
surface	149.6	4.2%	198.13	5.5%

The durations of the spatial relationships actions are investigated in order to understand what kind of spatial features the designers focused on. Table 8 shows the duration percentages of the spatial relationships actions in all the design sessions. In the RS session, the time spent on the spatial features of the design representation was limited (the highest percentage is 3.7 %, for the allocentric action), as shown in Table 8. We observed that the architects focused more on the alignment action (spatial adjacency of the design objects) in the 3D sessions (20.6%). The duration percentage of the egocentric referencing (3.1%) is high in the RS session. There is a drop in the duration percentages of the egocentric action, and there is an increase in the duration percentages of the allocentric action (7.8%) in the 3D session, as shown in Table 8.

TABLE 8: The durations of the perceptual focus on the spatial relationships action

Second - %	RS		3D	
alignment	95.07	2.6%	742	20.6%
arrangement	129.26	3.6%	444.47	12.3%
egocentric	110.3	3.1%	94	2.6%
allocentric	133.17	3.7%	280.54	7.8%

We suggest that designers tended to use more referencing in 3D modelling, and they focused on different visuo-spatial properties of the design representation in sketching and 3D modelling. This finding indicates that the designers developed a sense of presence in the virtual environments that might have an impact on their visuo-spatial reasoning. 3D virtual worlds are intended to create “the illusion of participation in a synthetic environment rather than external observation of such an environment” (Gigante 1993). Depending on the used external devices the 3D virtual environments could enable people to become “immersed in the experience” of interacting with the external representations (Kalawsky 1993). “The sense of immersion” is defined as the level of fidelity that virtual environments provide to the user's senses (Narayan et al. 2005), which could be enhanced with the use of human-shape characters (avatars) (Hoon et al. 2003). In our experiments, the 3D virtual world is the desktop systems wherein the designers are represented by the avatars. The avatars can fly, walk, sit and touch the objects, thus this real-life-like behaviour of the avatar creates an illusion of immersion.

5.3 Did They Solve The Design Problem And Act On The Design Representation At The Same Time?

After examining the designers' collaborative actions according to the coding categories, the relationships between some action categories are also provided in order to identify the role of different environments in structuring designers' collective thinking process and their interaction with the design representation. The categories of the actions are plotted on the same graph, which provides a representation of the segment length for each category along the timeline and is analysed visually. Each horizontal bar shows the beginning of the sessions, which are on the left and the durations of each action. The numbers 1 (Greg) and 2 (Lee) represent each designer's actions.

Figure 13 shows the communication about the design activity (the design process) and the visual acting on the representation (realisation action) categories along the timeline of the sessions. In the RS study, the design process and the realisation actions were parallel. This means that they spent time on analysing the problem, proposing design ideas and synthesising them while they were simultaneously sketching in Groupboard. In the virtual environment, there were segments that only included the realisation actions, marked with dotted circles, as shown in Figure 13. In particular, the design process actions were cut off in larger chunks and replaced with the realisation actions. This shows that in the RS study, the sketching (realisation action) was a parallel action to the design process actions. However, in the virtual environment, the realisation and the design process actions were not parallel actions for most of the time. The reason for this could be that the architects worked alone most of the time in the 3D virtual world, thus they might be occupied in working on their part of the design and they did not need to externalise their design ideas.

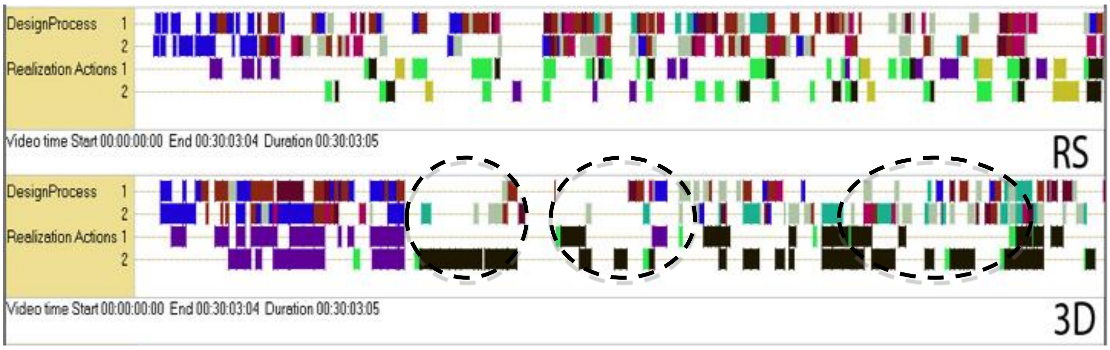

FIG. 13: The parallel actions: Collaborative design process and realisation actions

This finding suggest that the type of representation might have an impact on the designer's cognitive load, which is concerned with the limitations of working memory capacity. Studies show that design externalisations that are off-loaded from the 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.

During the designing activity, possible design solutions should be generated, elaborated and evaluated. Because of the limitations of human mental capacity (or the working memory) (Miller, 1956), designers rely on the external design representations as accessible data storages that reduce the information-processing load. As the findings indicate the designer's "conversations" with her/his mind and others are different in sketching and 3D modelling environments. The verbal externalisation of the design thoughts in sketching seems to be a spontaneous action; this means that designers sketch and talk about designing at the same time. In contrast, the graphical externalisation of the design thoughts in 3D modelling seems to be the dominant behaviour. This means that designers model with less talk.

Based on the finding, the question is raised: what is the reason for this difference? We suggest that: first, in the 3D virtual world, the designers had task divisions and each of them knew what to do next. So there would be no reason for talking; instead they focused on making their parts of the design model. Second, sketching is off-loading mental capacity and does not require extra mental processing, thus the designers have quick and frequent attention shifts and simultaneously verbalise design thoughts. Third, the designing in virtual worlds may load a designer's cognition and requires extra information processing. This extra cognitive load may slow them down. For that reason, they have longer and fewer attention shifts in 3D virtual worlds.

6. DISCUSSION

The protocols of the collaborative design sessions are segmented, encoded and analysed. The detailed analyses show that designing in virtual environments has an impact on the designers' collaborative design process, which can be categorised into the following ways: (1) the effects of shared view and design representation, and (2) the effects of being immersed in the environment.

6.1 The Changes Based On The Shared Visual Space

Our findings suggest that the shared visual spaces have an impact on designers' collaborative process (based on Kvan's (1997) model). The processes of the model were iterated many times during the collaborative sessions. Based on the verbal design protocols, the analysis shows that the designers kept working together and demonstrated iterations of negotiation and the evaluation actions many times during the remote sketching. The results of the protocol analysis show that the dynamic interface of the 3D virtual worlds encourages the designers to work in the individual mode. When the designers have the same view on the design representation, they work on the negotiation and the evaluation mode, and when the designers have a shared model but not the shared view, which they have in the 3D virtual worlds, the design model provides a basis for the meta-planning and the individual work, as well as a basis for the negotiation and critique. Having their own viewpoint and workspace in the collaborative virtual environments might have an effect on designers' collaborative design process, as it allows them to be apart and work separately. In addition, when individual work was involved in the collaborative design process, the meta-planning actions also occurred more frequently. This means that when the designers separated and worked individually, they monitored each other's actions/behaviour and their progress on the tasks. Thus, the collaboration became more structured and productive.

Most 2D-based multi-user systems support shared interfaces by presenting exactly the same image of the representation to all users: What You See Is What I See (WYSIWIS) (see He and Han 2006 for a review on WYSIWIS). The remote sketching application, Groupboard, also supports the WYSIWIS approach, except that the users have the ability to configure their shared user interface to best suit their working needs. In Groupboard, the design representation is a shared representation that provides a shared workspace, ensuring awareness of the drawing actions. In contrast, 3D virtual worlds that can be considered as shared three-dimensional interfaces provide a shared 3D space and all the users have a different viewpoint, which is not analogous to the use of WYSIWIS interfaces. Active Worlds allows individuals to move freely around the 3D workspace while still providing information about the shared design representation and the position of the others (via the presence of the avatars), but the technique of manipulating the design objects does not support workspace awareness. In AW, the designers are not able to see others modelling actions, unless the command is finalised. Therefore, maintaining collaboration and monitoring each other's actions become an issue.

The shared visual space included the communication channel, and the 2D-3D visual information that allows designers to work together on the shared representation. Our observations show that designers seem to be interested in the view of the design representation and the avatar and the designing tools and interfaces in the remove virtual environments, rather than seeing each other's face on the video screen. Thus, they closed the video channel window to enlarge their working space. The analysis of the protocol data demonstrates that remote sketching supports the WYSIWIS approach, except that the users have the ability to configure their shared user interface to best suit their working needs. The dynamic interface of the 3D virtual worlds encourages the designers to work in the individual mode. The findings of this paper indicate that there is a potential benefit to be gained from further research on the relationship between collaborative design activities and shared representation in collaborative virtual environments. Further work is needed to understand the role of shared view and representation in collaborative design, in particular, how they affect the team performance, participation and task management.

6.2 The Changes Based On The Designers' Sense Of Presence And Visuo-Spatial Features Of Design

The analysis of the protocols shows that the different design modes (sketching and 3D modelling) afford different perceptual focus on the spatial properties of the design solution: (1) the designers focused more on the visual features of the design object, which are size, form, colour and materials, while sketching, and (2) the designers focused on the spatial relationship of the design objects, which are spatial adjacency, arrangements, position, etc., while they design in 3D modelling mode. The reasons for this difference might be that the 2D and 3D representations have different properties, and they afford and "instil slightly different mental models" (Byrant and Tversky, 1999).

3D models convey all three spatial dimensions directly. In particular, the properties of the design representation: The three dimensions, the location, the relative position, and the depth cue, are expressed directly. 2D sketches may depict three-dimensional relations but they are two-dimensional. In sketches, designers use a number of conventions for conveying depth, size, height in a picture plane, as well as possibly using verbal and symbolic information to express spatial information.

The investigation of the designers' self-referencing has potentials to reveal the designers' perception of presence while they are designing in virtual environments. In the field of psychology, studies have pointed out that people tend to position themselves differently in diagrams and models (Bryant and Tversky 1999; Tversky 2005). For example, when learning from diagrams, participants adopted an outside point of view and imagined the scene rotating in front of them, and a 3D model encouraged participants to take the internal viewpoint of the object. Our analysis showed that there was an increase in the designers' referencing (both egocentric and allocentric) in 3D virtual worlds, and they tended to position themselves outside the design representation in sketching. It could be that because of the above different properties of the 2D-3D representations, the designers' perceptual focus was also different in sketching and 3D modelling.

We could suggest that the presence of the designer's body has an effect on designers' interaction with the representation and their perceptual focus. We could conclude that the experience of being immersed in a virtual world while designing is quite distinct from interacting with real-world artefacts. The 3D virtual worlds are intended to create "the illusion of participation in a synthetic environment rather than external observation of such an environment" (Gigante 1993). Depending on the used external devices[viii], the 3D virtual environments could enable people to become "immersed in the experience" of interacting with the external representations (Kalawsky 1993). "The sense of immersion" is defined as the level of fidelity that virtual environments provide to the user's senses (Narayan et al. 2005), which could be enhanced with the use of human-shape characters (avatars) (Hoon et al. 2003). In our experiments, the 3D virtual world is a desktop system wherein the designers are represented by the avatars. The avatars can fly, walk, sit and touch the objects, thus this real-life-like behaviour of the avatar creates an illusion of immersion.

Our examinations show that when designers were manipulating/modifying the 3D model they produced more perceptual focus actions. In particular, they articulated the spatial relationships of the design elements. In addition, the designers produced more low-level design exchanges and inferences about the structure in the 3D modelling environments.

The implications of the findings raise the question of what the cognitive benefits are of representing the design ideas at higher levels of realism, in comparison to higher levels of abstraction. Additional research is needed on whether the perceiving and acting in the 3D virtual worlds would provide better designing and collaboration experiences through the augmentation of spatial cognition. The potential benefits of 3D virtual worlds in enhancing designers' spatial cognition require further research.

7. CONCLUSION

We have studied two designers using virtual environments while designing together, allowing us to compare their behaviour and interaction within the environments. We conclude that designers adapt to different virtual environments showing different focus and interaction in each environment. The results of the study imply the following:

We found that the type of design representations affected the designers' collaborative behaviour. The sketching supported the designers' collaborative actions more than 3D modelling did. In sketching designers stayed in a co-design situation, wherein they negotiated and critiqued more on the functional issues, staying in high-level design ideas. Further, they usually took the perspective of a character outside the representation. 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 on the structural issues, staying in low-level design ideas.

The results of this research imply that (1) the use of sketches in design increased collaborative activities more than 3D modelling did, (2) the use of sketches increased the reasoning about the visual features of the design representation and the use of 3D modelling increased the reasoning about the spatial relationships of the design model, (3) 3D modelling slowed the designer down, thus resulting in fewer verbalisations, and (4) the architects designed the 3D models while they focused on different aspects in 3D modelling. Considering these differences, the research provides knowledge of the implications of the differences in collaborative design processes and designers' interaction with the representation, which can form the basis for guidelines on future developments in collaborative virtual environments.

The developments in collaboration and design technology are encouraging designers to consider new media for communication and designing; the cognitive impact of collaborative virtual environments on designing must therefore be addressed. This investigation needs to be repeated in the future as technologies and user familiarity improve with a larger sample size. This study has participated in this endeavour by bringing together theories and constructs from the diverse framework of design theory, computer-supported collaborative design, and virtual environments. Through such diversity, collaborative technologies are formulated and shaped and it will be through such diversity that their nature and effectiveness will be determined.

In addition, with the developments in advance communication and information technologies, the intention towards using these tools for communication and designing is becoming more common in the early stages of designing. The analyses of the collaborative design protocols provide a basis for a better understanding of the collaborative design cognition and the interaction with the design representation. The knowledge provided here could be useful for system developers and designers. System developers usually do not understand the early building design (Meniru, 2005) and design collaboration processes due to their lack of knowledge of the collaborative design process. In addition, designers could employ this knowledge to shape their decisions to use a particular technology in their practice. This knowledge will also have implications for both developments in future collaborative virtual environments and choosing an appropriate medium for designing.

8. ACKNOWLEDGEMENT

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9. REFERENCES

Achten, H. and Joosen, G. (2003). The Digital Design Process - Reflections on a Single Design Case. Digital Design, 21st eCAADe Conference Proceedings. Graz, Austria, 269-274.

Akın, Ö. and Lin, C. (1995).Design protocol data and novel design decisions. Design Studies, 16(2): 211-236.

Asimow, M. (1962). Introduction to Design. Englewood Cliffs, NJ, Prentice-Hall, Inc.

Arias, E., Eden, H., Fischer, G., Gorman, A. and Scharff, E. (2000). Transcending the Individual Human Mind-Creating Shared Understanding through Collaborative Design. ACM Transactions on Computer-Human Interaction, 7,(1), 84-113.

Atman, C.J. and Bursic, K.M. (1998). Verbal protocol analysis as a method to document engineering student design processes. Journal of Engineering Education, 87(2): 121-133.

Austin, J.L. (1962). How to Do Things with Words, Oxford, Clarendon Press.

Bryant, D.J. and Tversky, B. (1999). Mental Representations of Perspective and Spatial Relations From Diagrams and Models. Journal of Experimental Psychology: Learning, Memory, and Cognition, 25(1): 137-156.

Candy, L. and Edmonds, E.A. (1994). Artefacts and the Designer's Process: Implications for Computer Support Design. Revue Science et Techniques de la Conception, 3(1): 11-31.

Carroll, J.M., Thomas, J.C. and Malhortra, A. (1980). Presentation and Representation in Design Problem Solving. British Journal of Psychology, 71,143-153.

Chan, C.S. (2011). Design Representation and Perception in Virtual Environments. In Collaborative Design in Virtual Environments. Wang, X, Tsai, J (eds.), 29-40.

Cohen, M.R. (1944). A Preface Logic, New York, Henry Holt.

Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. Education and Psychological Measurement, 20,37-46.

Coyne, R.D., Rosenman, M.A., Radford, A.D., Balachandran, M. and Gero, J.S. (1990). Knowledge Based Design Systems, Massachusetts, Addison-Wesley, Reading.

Cross, N., Christiaans, H. and Dorst, K. (eds.). (1996). Analysing Design Activity, Chichester, UK: John Wiley and Sons.

Cross, N. (2007). From a Design Science to a Design Discipline: Understanding Designerly Ways of Knowing and Thinking, Design Research Now, ISBN 978-3764384715.

Darses, F., Detienne, F., Falzon, P. and Visser, W. (2001). A Method for Analysing Collective Design Processes. INRIA research report. France.

Ericsson, K. A. and Simon, H.A. (1984). Protocol Analysis: Verbal Reports as Data. Cambridge, MIT Press.

Finke, R., Ward, T. and Smith, S. (1992). Creative Cognition: Theory, Research and Application, Cambridge, MA, MIT Press.

Gabriel, G. and Maher, M.L. (1999). Coding and Modelling Communication in Architectural Collaborative Design.ACADIA' 99.

Gabriel, G.C. (2000). Computer Mediated Collaborative Design In Architecture: The Effects Of Communication Channels On Collaborative Design Communication, University of Sydney.

Gero, J. S. and McNeill,T. (1998). An Approach to the Analysis of Design Protocols. Design Studies, 19(1): 21-61.

Gigante, M. A. (1993). Virtual Reality: Definitions, History And Applications. Virtual Reality Systems. R. A. Earnshaw, M. A. Gigante and H. Jones (eds). London, Academic Press: 3-15.

Gül, L.F. (2007). Understanding Collaborative Design in Different Environments: Comparing Face-to-Face Sketching to Remote Sketching and 3D Virtual Worlds, Key Centre for Design Computing and Cognition, PhD Thesis, University of Sydney.

Gül, L.F. (2008). Affording Embodiment in Collaborative Virtual Environments: What is the Role of Presence in Collaborative Design? The 11th Annual International Workshop on Presence, Presence 2008, ISBN 978-88-6129-287-1, 16-18 October 2008, Padova, Italy, p.297-304.

Gül, L.F. (2009a). Evaluating Design Behavior When Using Emerging Collaboration Technologies, International Journal of Architectural Engineering and Design Management, Vol.5 Number 3, p.107-123.

Gül, L.F. and Maher, M.L. (2009b). Co-Creating External Design Representations: Comparing Face-To-Face Sketching to Designing in Virtual Environments, International Journal of Co-Design in Design and the Arts, Vol. 5, Issue 2, p. 117 – 138.

He, F. and Han, S. (2006). A Method And Tool For Human-Human Interaction And Instant Collaboration In CSCW-Based CAD. Computers In Industry, 57: 740-751.

Heiser, J., Tversky, B. and Silverman, M. (2004). Sketches for and from Collaboration. In Gero, JS, Tversky, B and Knight, T. (eds.) Visual and Spatial Reasoning in Design I. Sydney: Key Centre for Design Research. 69-78.

Hennessy, S. and Murphy, P. (1999). The Potential For Collaborative Problem Solving In Design And Technology. International Journal Of Technology And Design Education, 9: 1-36.

Hesse, M. (1966). Models and Analogies in Science. University of Notre Dame Press, Indiana.

Hoon, M, Jabi, WM and Goldman, G. (2003).Immersion, Interaction and Collaboration in Architectural Design Using Gaming Engines. CAADRI 2003. 721-738.

International Society for Presence Research (2000). The Concept of Presence: Explication Statement http://ispr.info/.

Kalay, YE (2001). Enhancing Multi-Disciplinary Collaboration through Semantically Rich Representation. Automation in Construction, 10,(6), 741-755.

Kalawsky, R. S. (1993). The Science Of Virtual Reality And Virtual Environments. Workingham, Addison-Wesley.

Kvan, T. (2000). Collaborative design: what is it? Automation in Construction, 9(4): 409-415.

Kvan, T, West, R and Vera, A. (1997). Tools and Channels of Communication: Dealing with the Effects of Computer Mediation on Design Communication. 1st International Conference on Creative Collaboration in Virtual Communities. University of Sydney.

Lugt, Rvd (2005). How Sketching Can Affect the Idea Generation Process in Design Group Meetings. Design Studies, 26,101-122.

Maher, ML, Bilda, Z, Gu, N, Gül, LF, Huang, Y, Kim, MJ, Maher, ML, Marchant, D and Namprempree, K. (2005). Collaborative Processes: Research Report on Use of Virtual Environment. Sydney: the University of Sydney.

McBride, G. (2005). Using Statistical Methods for Water Quality Management: Issues, Problems and Solutions., New York, Wiley.

Mc Neill, T. (1999). The Anatomy of Conceptual Electronic Design. PhD Doctoral Dissertation, University of South Australia.

McNeill, T., J. S. Gero, et al. (1998).Understanding Conceptual Electronic Design Using Protocol Analysis. Research in Engineering Design, 10: 129-140.

Meniru, K.C.U. (2005). Computer-Aided Conceptual Building Design. Ph.D. Thesis, Centre for Building Studies, Concordia University, Montréal, Canada.

Narayan, M, Waugh, L, Zhang, X, Bafna, P and Bowman, D. (2005). Collaboration and Cooperation: Quantifying the Benefits of Immersion for Collaboration in Virtual Environments. The ACM Symposium on Virtual Reality Software and Technology (VRST'05). ACM Press, 78-81.

Oxman, R., O. Palmon, et al. (2004). Beyond The Reality Syndrome: Designing Presence In Virtual Environments. SIGRADI 2004 - [Proceedings Of The 8th Iberoamerican Congress Of Digital Graphics], Porte Alegre - Brasil.

Perrya, M and Sanderson, D (1998). Coordinating Joint Design Work: The Role of Communication and Artefacts. Design Studies, 19,(3), 273-288.

Robertson, T (1996). Embodied Actions in Time and Place: The Cooperative Design of a Multimedia Educational Computer Game. CSCW, 5,(4), 341-367.

Remko, vdL. (2002). Functions of Sketching in Design Idea Generation Meetings.CandC'02.Loughborough, Leic, UK: ACM.

Peng, C. (1994). Exploring Communication in Collaborative Design: Co-Operative Architectural Modelling. Design Studies, 15,(1), 19-44.

Porter, T. and Neale, J. (2000). Architectural Supermodels, Oxford, Architectural Press.

Rittel, H. and Webber, M.M. (1984). Planning Problems Are Wicked Problems. Developments In Design Methodology, New York, John Wiley And Sons, Inc.: 135-144.

Purcell, AT, Gero, JS, Edward, H and Mc Neil, T. (1996). The Data in Design Protocols: The Issues of Data Coding, Data Analysis in the Development of Models of the Design Process. in Cross, N andChristiaans, H (eds.) Analysing Design Activity. Chichester, UK: John Wiley and Sons Ltd. 225-252.

Schön, D. A. (1984). Problems, frames and perspectives on designing. Design Studies, 5(3): 132-136.

Schön, D.A.and Wiggins, G (1992). Kinds of Seeing and Their Functions in Designing. Design Studies, 13,(2), 135.

Scrivener, SAR, Clark, SM, Clark, A, Connolly, J, Garner, S, Palmen, H, Schappo, S and Smyth, MG. (1992). Rococo: Phase 1 Report. LUTCHI Research Centre, Loughborough University.

Searle, JR. (1969). Speech Acts, London, Cambridge Press University.

Seitamaa-Hakkarainen, P, Lahti, H, Muukkonen, H and Hakkarainen, K. (2000).Collaborative Designing in a Networked Learning Environment. in Scrivener, SAR, Ball, LJ and Woocock, A (eds.) Collaborative Design. London: Springer-Verlag. 411-420.

Simon, H. A. (1969). The Science Of Artificial. Cambridge, MA, The MIT Press.

Suwa, M. and B. Tversky (1997).What do architects and students perceive in their design sketches? A protocol analysis. Design Studies, 18(4): 385-404.

Suwa, M, Gero, J and Purcell, T (2000). Unexpected Discoveries and S-Invention of Design Requirements: Important Vehicles for a Design Process. Design Studies, 21,(6), 539-567.

Suwa, M, Tversky, B, Gero, J.S. and Purcell, A.T. (2001). Seeing into Sketches: Regrouping Parts Encourages New Interpretations. inGero, JS, Tversky, B and Purcell, AT (eds.) Visual and Spatial Reasoning in Design II. Sydney: Key Centre of Design Computing and Cognition, University of Sydney.

Tversky, B. (2005a). Functional Significance of Visuo-spatial Representations. Handbook of Higher-Level Visuo-Spatial Thinking. P. Shah and A. Miyake. Cambridge, Cambridge University Press: 1-34.

Tversky, B. (2005b). Visuo-Spatial Reasoning. Chapter 10. The Cambridge Handbook Of Thinking and Reasoning. K. Holyoak and R. Morrison. Cambridge, MA, Cambridge University Press: 472-548.

Watts, R.D., Ed. (1966). The Elements of Design. The Design Method. Butterworths, London.

Williams, A (2002). Architectural Modelling as a Form of Research. Architectural Quarterly, 6,(4), 337-347.

[i] www.mimio.com
[ii] http://www2.smarttech.com/st/en-US/Products/SMART+Boards/Overlays/Default.htm
[iii] AA was developed by Adobe Systems and was discontinued.
[iv] www.blaxxun.com
[v] www.virtools.com
[vi] VW was developed by Microsoft Research and was discontinued.

[vii] See www.mangold.de and www.behavioral-research.com for Interact software.

[viii] Images could be displayed stereoscopically to the user, via head-mounted display. There is no taxonomy of types of virtual reality immersion. Most virtual reality classification is based on the types of graphical techniques used for rendering three-dimensional objects and in terms of applications that may benefit from being represented in virtual reality.