Co-creating external design representations: Comparing face-to-face sketching to designing in virtual environments

L.F. Güld and M.L. Maher

aSchool of Architecture and Built Environment, University of Newcastle, Newcastle, Australia; bKey Centre of Design Computing and Cognition, University of Sydney, Sydney, Australia

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While developments in computer-supported collaborative work tools, computer aided design and the availability of high bandwidth networks offer alternative collaborative environments for design, the alternatives have yet to be characterised in terms of their impact on the co-creation of a shared model. A specific collaborative design environment makes a commitment to the way in which the designers can communicate and co-create an external representation of the shared design model. This research focuses on the impact of alternative collaborative virtual environments on design behaviour and collaborative processes. An experiment was conducted to identify similarities and differences between co-located collaborative designing using sketches as the external representation and remote collaborative designing sessions using sketches and 3-D models. The results of this study are discussed in terms of: (1) the effect of being remotely located; (2) the effect of the type of external representations.

Keywords: collaborative design; protocol analysis; external design representation; sketching; 3-D modelling; virtual worlds

1. Introduction

The developments in and the extensive use of Internet technologies have brought about fundamental changes in the way architecture, engineering and construction (AEC) professionals collaborate and design. This change has been to improve efficiency and, due to the global nature of the industry, the need for communication and collaboration between AEC professionals using various computer-mediated technologies. Thus, computer-mediated communication technologies have become a vital medium for large design firms. In the past two decades, a variety of disciplines have participated in implementing, testing and developing information technology tools that are designed to address human collaboration at work, commonly known as Computer Supported Collaborative Work systems. Although these developments have led to important advances in the enabling technologies that are required to support the changes in design practice, very little is known about the role and the impact of these technologies on design collaboration and how different types of digital design media affect architects’ co-creation of the design representation.
Collaborative design 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 (Hennessy and Murphy 1999, Seitamaa-Hakkarainen et al. 2000). Collaborative design activity requires sharing information and organising design tasks and resources (Chiu 2002). This paper analyses verbal and visual design protocols in a collaborative design context, based on the assumption that communication through conversation and interaction with the external representation in the design environment provides some insight into the effect of different external representations on collaborating designers’ behaviour and processes.

The aim of the study is to identify the changes in collaborating designers’ behaviour and processes when they move from co-located sketching to remote designing. In particular, what are the differences and similarities in: (1) the design process while co-creating the external design representation? (2) the shared activities, in particular, how does the type of external representation affect actions of co-creation of the external design representation in virtual environments?

2. Understanding the role of external representations in design

Designers employ various types of external representation, such as sketches, physical and digital geometric models, diagrams, graphs, notations and object properties. Interaction with an external representation is a way to externalise a mental representation for reflection and extension. 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 (Akın and Lin 1995, Goel 1995). Akın (1982) pointed out the importance of the external design representation in facilitating the formulation of a mental representation of a design idea as well as the communication of design ideas. Akın (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’ (p. 2).

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

External design representations enable a dialogue between the designer and her/himself (Schön and Wiggins 1992). According to Schön’s theory (1983) design is a ‘reflective conversation with the situation’ (p. 76). 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 has a conversation with the drawing. The term ‘conversation’, referring to the designers’ internal processing, includes 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 uses visual thinking to deal with pictorial properties of design concepts. She divided the design process into moves and arguments that had two types: ‘seeing as’ and ‘seeing that’. She said that the process of sketching was a systematic dialectic between the ‘seeing as’ and ‘seeing that’ reasoning modalities. The designer was ‘seeing as’ when she/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.

Designers rely on external design representations for communicating design ideas not only to themselves but also to others. Researchers have studied how designers
use design representations to facilitate design thinking and the relationship between the design process and design outcome (Atman and Bursic 1998). Ullman et al. (1990) reports that sketches can be interpreted at different levels of abstraction and provide an external memory to aid the designer. In their protocol studies, Kavaklı et al. (1998) confirm that designers sketch objects part by part rather than as a whole. Others suggest 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 Hennessey 1998). In the engineering domain, Cardella et al. (2006) confirm 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 sketch and examine sketches to discover visual cues that suggest ways to refine and revise the design ideas (Suwa and Tversky 2002). This cycle of sketch–inspect–revise is similar to Schön and Wiggins’s (1992) reflective conversation.

Most of the above views are based on studies that examine individual designers’ sketching activity using paper and pencil environments. In the present study, sketching is the baseline for characterising the changes in the designers’ interaction with the external design representation while collaborating in different virtual environments. The impact of different types of external design representations is explored, both sketches and 3-D models, and the type of environment, both face-to-face and virtual, on collaborating designers’ behaviours and processes.

2.1. External representations in collaborative design

In the field of collaborative design, one of the topics of interest is the provision of a more efficient communication process. External design 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 oneself and with others.

Most importantly, these external representations become the ground on which conflicts and collaboration take place. Recognising the need for externalisation in collaborative design, Norman (1993) defined the distributed cognition that occurs not only in the individual’s mind in isolation, but also in the interaction of the mind with tools and artefacts as well as groups of minds in interaction with each other (as cited in Arias et al. 2000). Arias et al. (2000) put forward that the externalisations were especially important for collaborative design, because design 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); (3) form the basis for critique and negotiation (Arias et al. 2000).

2.2. Shared creation of the representation

Another view of collaboration examines the concurrency of designers’ actions on the design representation. Kvan (2000) presents a framework that divides collaborative design into two: loosely coupled and closely coupled. According to Kvan (2000),
although there is a common suggestion that collaborative design activity is an ongoing closely coupled process in which the designers work together all the time, experience says that much design is loosely coupled, during which each designer works separately. The ratio of loosely coupled and closely coupled design activities may be affected by the type of shared external representation in a virtual environment.

When designers externalise their ideas with a combination of words, sketches and gestures (Bly 1988, Tang 1989, Neilson and Lee 1994), as well as references to other objects or shared experiences (Eckert and Stacey 2000), and their colleagues respond to what they see, interpreting vague or ambiguous objects and then negotiate over their intended meaning, new ideas can be derived and problems with the existing design can be found (Eckert and Boujut 2003). Since different design representations convey meaning in different ways, the nature of the shared external representation may affect the activities and duration of specific processes of design collaboration.

3. Studying interaction with the design representation in collaborative design

An experiment was conducted to characterise and identify the impact of the different external representations that arise in new virtual environments. The present study focuses on two specific types of external design representations: sketches and 3-D models. The interaction with the design representation was analysed, searching for three kinds of activities: (1) engagement with the design representation; (2) individual actions to create representations; (3) shared activities to co-create representations.

A baseline in a face-to-face environment was established, in which the designers collaborate by sketching using pencil and paper. Designers collaborating in three different virtual environments comprise the comparison data. For the comparison, protocol data were collected from remote design collaboration in three scenarios: remote sketching; remote 3-D modelling; remote 3-D modelling with sketching. (The empirical data that are used in this paper were collected for a research project, ‘Team collaboration in high bandwidth virtual environments’ and were provided by the Cooperative Research Centre for Construction Innovation (CRC CI). The results of this research have been published in several conferences (Maher et al. 2005a,b, 2006). With a different research focus, this paper analyses a subset of experiment sessions of the CRC CI study).

Since the design sessions vary across two conditions: co-located vs. remote and sketching vs. 3D, the comparison makes it possible to consider the impact of change in each condition separately or together.

3.1. Experimental set up and procedures

3.1.1. Baseline study

The aim of the baseline study is to characterise the collaborative design process when the designers are using traditional materials, pen, paper, scale, etc., and without digital systems for designing and communication, as shown in Figure 1.

In the baseline study, two architects collaborate on a design task while sketching together around a table and developing a design representation using pen and paper. They were asked to design a contemporary art gallery that includes permanent and temporary exhibition halls, a sculpture space, art store, services and offices. A video
of their design actions and communications was captured with a digital video recording (DVR) system (16 channel Ness digital video recorder; St Paul, MN).

3.1.2. Comparison study
The aim of the comparison study is to compare three collaborative design sessions with the baseline study (FTF): (1) FTF and remote sketching (RS); (2) FTF and 3-D virtual world (3-D); (3) FTF and 3-D virtual world with sketching (3-DS). The key objective of the study is to characterise the differences and similarities between the design environments for collaborative design and FTF paper sketching. Figure 2 shows the DVR views of the three experiments in which the architects were collaborating. The designers were located in the same room with a panel between them to simulate high bandwidth audio communication. The same architects were given different tasks of similar complexity in each setting. Similar to the baseline study, their actions and communication were recorded by a DVR system.

In the RS session, the architects used a shared whiteboard application (Group Board) and digital pen interfaces (Mimio and Smart Board), as illustrated in Figure 2.

Figure 1. The baseline study, face-to-face design session.

Figure 2. The comparison study, two designers collaborating within three different collaborative virtual environments: (a) RS-Group Board; (b) 3D-Active Worlds; (c) 3DS-DesignWorld. RS = remote sketching; 3D = 3D virtual world; 3DS = 3D virtual world with sketching.
Mimio and Smart Board are 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 were asked to design a contemporary library, which includes a foyer, open
access bookshelves, reading area, loan desk, offices, audio-visual library, a small
theatre and services.

In the 3-D virtual world (3-D) session, the architects designed in Active Worlds
using a typical desktop system with mouse, keyboard and a monitor, as shown in
Figure 2. In the 3-D session, they were asked to design a fine arts and dance school,
which includes studio spaces, offices, foyer, amenities, services and café. Active
Worlds offers ‘library-based’ design. In a typical library-based design, the objects are
predefined outside the world and are provided in the object library of the design
platform. Modification of the shapes and forms of the objects require an object
library update, which was not available to the designers in this study. A set of design
elements (walls, slabs, space objects and columns) and navigation signs were
provided at the entrance of the site.

In the 3-D virtual world with sketching (3-DS) session, the architects used a
prototype system, Design World (This prototype was developed as part of the CRC CI
project), which includes a 3-D virtual world (Second Life) augmented with a
collaborative sketching tool (Group Board) (see Maher et al. 2005a, for more detail on
the system) as shown in Figure 2. In the 3-DS session, the architects were asked to
design a shopping arcade and a tower, which includes a viewing platform, restaurants,
shops, amenities and services. Design World is implemented in Second Life, which
provides facilities for parametric modelling. A parametric design includes a set of
objects whose forms are determined inside the world by selecting geometric types and
manipulating their parameters. Similar to Active Worlds, designers were represented
by avatars in Second Life (see Gül and Maher 2006, 2007).

3.2. Protocol coding scheme
Protocol analysis, which was first adopted by Eastman (1968) to study design
cognition, has been accepted as a research technique allowing for the clarification of
designers’ cognitive abilities (Cross 2001). A protocol analysis involves capturing data
about or during the design process and coding the data in order to analyse the
occurrence and order of different types of activities. The expected result of the study is
that different virtual environments will affect the ways in which the designers interact
with the design representation. Thus, measuring the changes in the interaction with the
design representation is necessary. The main category, interaction with the design
representation, includes the verbalisation and the visualisation of the external
design representations (the verbal-visual design protocols) produced to communicate
design ideas with her/himself and/or to others. The coding scheme is developed
based on relevant coding schemes in existing literature as well as on the observations
made from a previous study: the ‘CRC CI study’ (Maher et al. 2005b). The coding
scheme for the interaction with the design representation has six categories that
are further divided into sub-categories: the perceptual focus, the agent’s actions,
the collaboration mode, the representation mode, the realisation, the design
space mode. The yellow shaded codes existed in the CRC CI study, as shown in
Figure 3.

The coding scheme for interaction with the design representation captures: (1)
how architects create the external design representation (visual actions such as
(1) sketching, writing or modelling); (2) how they approach construction of the design representation (verbally articulating ideas for creating the design representation); (3) how they use visual information and how they inspect/interact with the interface/tools, given materials and the representation; (4) what visuo-spatial features of the representation they focus on, as shown in Table 1. This paper focuses on the results of realisation, design space, representation mode and collaboration mode categories since these highlight the impact of different types of external representation on the collaborating designers’ actions and design processes.

The first category is the realisation, which includes two sub-categories: the realisation actions and the realisation process. The realisation actions shares characteristics of Maher et al.’s (2005b) operations on representation coding scheme, Kavaklı and Gero’s (2001) analysis of concurrent cognitive actions and Cardella et al.’s (2006) representation coding scheme. The realisation actions category looks at the visual design protocol to capture the actions of the architects to create the design representation. The design representations are the drawings/sketches in the FTF and RS sessions and are the 3-D models in the 3-D and 3-DS sessions. This sub-category has the following codes: write, create elements, continue elements and delete elements, as shown in Table 2.

The realisation process has three codes: the decision, the modelling and the describe actions. The first two actions are the adaptation of Atman and Bursic’s (1998) design step category. The aim of the realisation process sub-category is to capture the discussions held between designers related to the concretisation of the design ideas. Atman and Bursic (1998) defined that the decision action referred to selecting an idea among alternatives, and the modelling action referred to describing how to build an idea and doing measurements and calculations. The modelling action also consists of idea generations about how to do the sketching and building the model. In this paper, sketching activity is considered as a somewhat abstract form of design modelling, based on Tjalve et al.’s (1979) description of sketching. In addition to those two codes, the describe action, which refers to defining/describing the design solution to others in a collaborative design context, is also included, as shown in Table 3.

Figure 3. A hierarchical tree of the interaction with the design representation coding scheme.
Table 1. The coding scheme for interaction with the design representation.

<table>
<thead>
<tr>
<th>Types of data Interaction with design representation</th>
<th>Verbal and Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptions</strong></td>
<td></td>
</tr>
<tr>
<td>Realisation</td>
<td>Capturing discussions and actions about concretisations of design ideas: (1) Realisation action: create – write – continue – delete; (2) Realisation process: modelling – describe – decision (borrowed from Atman and Bursic 1998).</td>
</tr>
<tr>
<td><strong>Agents Actions</strong></td>
<td></td>
</tr>
<tr>
<td>Capturing discussions and actions that are related to designers’ engagements with the surrounding space: onTools – onElements – gesture</td>
<td></td>
</tr>
<tr>
<td><strong>Perceptual focus</strong></td>
<td></td>
</tr>
<tr>
<td>Capturing discussions and actions that are related to visual features/form articulation and spatial relationships of the design elements: spatial relationships – object/entity</td>
<td></td>
</tr>
<tr>
<td><strong>Design Space</strong></td>
<td></td>
</tr>
<tr>
<td>Capturing discussions that are related to dimensions of design space: 2-D–3-D</td>
<td></td>
</tr>
<tr>
<td><strong>Representation Mode</strong></td>
<td></td>
</tr>
<tr>
<td>Capturing actions that are related to the types of representation used: 2-D–3-D (adapted from Maher et al. 2006)</td>
<td></td>
</tr>
<tr>
<td><strong>Collaboration mode</strong></td>
<td></td>
</tr>
<tr>
<td>Capturing actions that are related to shared representation activities: meeting – individual (borrowed from Kvan et al. 1997).</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The realisation actions category.

<table>
<thead>
<tr>
<th>Realisation actions</th>
<th>Visual data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Write</td>
<td>Creating a written response or writing down/listing ideas to be used later</td>
</tr>
<tr>
<td>Create elements</td>
<td>Engaging with (creating/drawing) point, line, plane, volume or in the 3-D virtual world: copying, cloning, duplicating an object</td>
</tr>
<tr>
<td>Continue elements</td>
<td>Continuing sketching (shading, colouring, tracing over) or modelling/developing the same representation further (modifying, moving, rotating, transferring, grouping)</td>
</tr>
<tr>
<td>Delete elements</td>
<td>Erasing elements/design object</td>
</tr>
</tbody>
</table>

The design space category captures the interaction/engagement of designers with the design space, which has two modes: Int_2-D and Int_3-D, as illustrated in Table 4. Based on observations from the experiment sessions, it was determined that there is a change in the designers’ articulation of the design dimensions in different environments. The Int_2-D space code refers to the discussions that are related to the construction of the 2-D shapes, geometries, relations and arrangements. The Int_3-D space code refers to the discussions that are related to the construction of the 3-D shapes, geometries, relations and arrangements.

The design representation mode has two codes: Rep_2-D and Rep_3-D, adapted from Maher et al.’s (2006) representation mode, as shown in Table 5. The representation mode captures the designers’ realisation activities with/in the 2-D and the 3-D representations. When the designers are using the 2-D representation (pen–paper and shared whiteboard) that is for writing and/or sketching, the segment is coded as Rep_2-D. When the designers are using the 3-D representations/virtual worlds, the segment is coded as Rep_3-D. The code
Rep_2-D is used to refer to the nature of the external representation and does not distinguish whether the designers’ sketches are 2-D plans/elevations or 3-D perspectives.

The last sub-category, collaboration mode, captures the shared activities of the designers to create the design representation. The collaboration mode includes two codes: the individual and the meeting, as shown in Table 6. The collaboration mode category is adapted from Kvan et al.’s (1997) description of the close-coupled and the loose-coupled processes. In the close-coupled process, the participants work intensely with one another, observing and understanding each other’s moves, the reasoning behind them and the intentions. In the loose-coupled process, the participants work separately on the agreed-upon parts and then they put them together. While there are many other modes of collaboration, the researchers focused on these two modes in order to highlight differences observed when the designers are collaborating in a 3-D world as avatars. The individual and the meeting codes are only determined by examining the video data in this study. With this interpretation of Kvan et al.’s (1997) definition of the loose-coupled and close-coupled process, the aim of the collaboration mode is to capture the nature of the shared activities for the creation of the design representation in the different environments. Maher et al. (2006) also used these definitions with a slightly different interpretation.

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### Table 3. The realisation process actions.

<table>
<thead>
<tr>
<th>Realisation process</th>
<th>Verbal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling</td>
<td>Modelling, describing how to build an idea, how to make it and discussing properties such as form material, dimension, surface … etc.</td>
</tr>
<tr>
<td>Decision</td>
<td>Select one idea or solution among other alternatives.</td>
</tr>
<tr>
<td>Describe</td>
<td>Define the design/design elements/locations … etc. to others.</td>
</tr>
</tbody>
</table>

### Table 4. The design space mode.

<table>
<thead>
<tr>
<th>Design space mode</th>
<th>Verbal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int_2-D</td>
<td>Interacting with 2-D space/ideas that are related to the 2-D, forms, geometry, texture and colour. Horizontal spatial arrangements</td>
</tr>
<tr>
<td>Int_3D</td>
<td>Interacting with 3-D space/ideas that are related to 3-D, view from different level, access of the sun and view from the atrium. Vertical spatial arrangements</td>
</tr>
</tbody>
</table>

### Table 5. The representation mode.

<table>
<thead>
<tr>
<th>Representation mode</th>
<th>Visual data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep_2-D</td>
<td>Acting in 2-D, sketching/writing in 2-D representation</td>
</tr>
<tr>
<td>Rep_3-D</td>
<td>Acting in 3-D, modelling in 3-D representation</td>
</tr>
</tbody>
</table>
3.3. Segmentation

During segmentation, the design protocol data are divided into smaller units. The protocol data consist 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, the protocols were first segmented using the utterance-based segmentation method as used in (Gabriel 2000, Maher et al. 2005b). In order to separate the utterances into meaningful units, which can be coded under a specific category relating to the design processes and actions, each utterance was segmented further using the actions-and-intentions segmentation method used in McNeill et al. (1998). Following the first run of the segmentation, which is based on the utterances, the researchers look for segments of data with no verbalisation containing visual actions and intentions based on the McNeil et al. definition.

Each segment can include combinations of visual and verbal design protocol data: (1) having verbal data only when there is no visual action; (2) having visual actions only when there is no verbal data; (3) having both the verbal data and visual action when designers talk and sketch/model at the same time in a segment. Table 7 shows one segment of the designers’ protocol data, taken from the baseline study (FTF). As illustrated in Table 7, the verbal data and visual action can happen at the same time, as shown in segments 78 and 80, but sometimes a segment has only verbal data, as shown in segment 79.

The segments are individually coded by two coders and a final coding is achieved using a process of arbitration, adapting the Delphi method (see McNeill 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 application (see www.mangold.de and www.behavioral-research.com for Interact software) is used to facilitate the segmentation and coding of the video sessions.

4. Results

To understand qualitative differences between the design environments, the encoded protocols were compared. Encoded protocols represent the context of collaborative designing, how designers collaborate and communicate and what kind of interactions they have 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 explored visually through the timeline graphs.
4.1. Overview of the protocol data

The attention changes/shifts are examined by an analysis of the segment durations in each session, as shown in Table 8. Since the continuous stream of data were segmented according to a change in the verbal or visual design protocols, the numbers of segments in each session provide information about how frequently the changes/shifts occurred. In the baseline study (FTF), the mean (M) duration of segments is the shortest (M 11.64 second) and the number of segments is the highest (182 count). As the designers moved to remote collaboration with video contact and then avatars, the segment durations increased and the number of segments decreased progressively, as shown in Table 8. The longest segment durations (56.5 and 123.5 second) are observed in the virtual world environments: the 3-D and the 3-DS.
sessions. The higher standard deviation values in the comparison studies show this tendency towards longer segments in the virtual world. The segment durations for all sessions are positively skewed, as illustrated in Table 8. The high kurtosis values show that the distribution of the durations of segments is peaked and the tails of the distribution are fat. This result shows that the designers experienced more attention shifts in the baseline study (less time and more segments) and they had less and longer attention shifts in the virtual environments.

The distribution of the segment durations along the segment numbers for one of the design sessions is shown in Figure 4. (For this pair of designers, the lowest number of segments is 165 in the 3-DS session, so only the first 165 segments are shown for all sessions.) These data demonstrate that the segment durations are longer in the virtual environments and shorter in the baseline study, for this pair of designers. This overview of the segment durations suggests that the designers had more new actions and shifted them quickly in the baseline study and they spent more time on an action before they engaged in a new action in the virtual environments.

These consistent data showing longer segment duration in the remote environments may be due to: (1) the remote environments slowed the designers down because the software introduced additional cognitive load and/or (2) the designers pursued each action in more detail in a digital representation than on paper.

### 4.2. Realisation actions to create external design representations

Figure 5 shows the duration percentages of the designers’ realisation actions comparing the baseline study with the virtual environments. These are the average duration percentages of the two architects collaborating in the four different design environments. The duration of each category is divided by the total elapsed time for each design session. Then the duration percentages for each category are calculated. As shown in Figure 5a, in the baseline study, the duration percentages of the ‘create’ and the ‘write’ actions are higher than the ‘continue’ and ‘delete’ actions, when the designers spent time on writing down the areas and listing the requirements, and on drawing the design solution. In the RS session, there is an overall increase in the duration percentages of the realisation actions, in which the duration percentages of the ‘create’ action are higher, compared to the baseline study, as shown in Figure 5a. The duration percentages of the ‘continue element’ action is high in the 3-D virtual worlds, as shown in Figure 5b,c.

### Table 8. Statistics on the duration of segments.

<table>
<thead>
<tr>
<th></th>
<th>FTF</th>
<th>RS</th>
<th>3-D</th>
<th>3-DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (seconds)</td>
<td>11.64</td>
<td>12.15</td>
<td>12.84</td>
<td>16.25</td>
</tr>
<tr>
<td>SD</td>
<td>5.55</td>
<td>5.73</td>
<td>7.76</td>
<td>11.21</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1.13</td>
<td>1.25</td>
<td>8.00</td>
<td>19.35</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.82</td>
<td>0.99</td>
<td>2.25</td>
<td>2.95</td>
</tr>
<tr>
<td>Minimum (second)</td>
<td>0.97</td>
<td>1.80</td>
<td>1.90</td>
<td>1.53</td>
</tr>
<tr>
<td>Maximum (second)</td>
<td>36.03</td>
<td>31.10</td>
<td>56.50</td>
<td>123.53</td>
</tr>
<tr>
<td>Segment count (mean)</td>
<td>182</td>
<td>176</td>
<td>168</td>
<td>139</td>
</tr>
</tbody>
</table>

FTF = baseline study; RS = remote sketching; 3-D = 3-D virtual world; 3-DS = 3-D virtual world with sketching.
Figure 4. The distribution of the segment durations: (a) Baseline study (FTF) and remote sketching (RS); (b) FTF and 3D virtual world (3D); (c) FTF and 3D virtual world with sketching (3DS).

Figure 5. The duration percentages of the realisation actions: (a) Baseline study (FTF) and remote sketching (RS); (b) FTF and 3D virtual world (3D); (c) FTF and 3D virtual world with sketching (3DS).
The realisation actions are shown along the timeline of the sessions in Figure 6. 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 the baseline study, the designers started with the write action and iterated the write–create actions during the session and they demonstrated some continue actions towards the end. In addition, the realisation actions occurred in smaller chunks, as shown in Figure 6. In the RS session, more frequent realisation actions patterns took place, except that some of the delete action occurred during the second half of the session. In the 3-D and 3-DS sessions, the designers showed different patterns in the realisation actions, compared to the baseline study. In the 3-D virtual worlds, the designers exhibited longer and more frequent continue actions in the second half of the sessions. In addition, they used the create action less frequently, as shown in Figure 6. This demonstrates that the designers engaged more with the modifying/moving objects in 3-D virtual worlds than with creating new objects. These results reflect the affordances in the different environments: the actions to modify and move objects are well supported in a 3-D virtual world.

4.3. Realisation processes to create external design representations

Figure 7 shows the duration percentages of the realisation process actions of the designers comparing the baseline study with the virtual environments. In the baseline study (FTF), the duration percentages of the decision and the modelling actions are high (the duration percentages are also very close) and the duration percentage of the describing action is less. In the remote environments, the duration percentages of
the modelling action are high and the duration percentages of the decision and the describing actions are low, compared to the baseline study, as illustrated in Figure 7a,b,c. This shows that, in the baseline study, making calculations, discussing programme components and discussing the properties of the design solution took place while the designers were choosing between the design concepts to pursue. These results also show that the main realisation issue in the virtual environments was how to represent the ideas and how to model/draw the design solution.

4.4. Interaction with the 2-D–3-D space

The design space actions are shown along the timeline of the sessions in Figure 8. In the baseline study, the architects discussed the 2-D aspect of the design representation during the session and later they discussed the 3-D aspect of the design more frequently. Similar to the baseline study, the RS timeline shows that the 2-D engagement action was frequent and longer than the 3-D engagement action at

![Figure 7. The duration percentages of the realisation process actions: (a) Baseline study (FTF) and remote sketching (RS); (b) FTF and 3D virtual world (3D); (c) FTF and 3D virtual world with sketching (3DS).](image)

![Figure 8. The design space actions over time. FTF = baseline study; RS = remote sketching; 3D = 3D virtual world; 3DS = 3D virtual world with sketching.](image)
the beginning of the session. This sequence is typical in design practice. The designing activity usually starts with 2-D shape articulations and making notations indicating the main concepts. Once there is an agreement on the concept, designers usually start to think about the 3-D aspect of the design idea, accompanied by drawing perspectives and elevations in the latter stage. In the 3-D and 3-DS sessions, a different pattern of behaviour was observed when the 2-D and 3-D engagement actions were compared to the baseline study: the designers exhibited longer chunks of the 2-D engagement action at the beginning of the sessions in the 3-D virtual worlds and later they engaged in longer and more frequent 3-D engagement actions, as illustrated in Figure 8. They talked about the vertical relationships of the spaces and circulations, views from the different slabs and the overall proportion of the model, etc.

4.5. Interaction with the types of representation

The design representation actions are shown along the timeline of the sessions in Figure 9. As expected in the baseline study, the designers used the site plan and papers (2-D representation) during the session. Similarly in the RS session, the designers demonstrated 2-D_rep actions. In the 3-D session, first the designers exhibited the 2-D_rep actions, in which they used the given design brief to write/list some notes and make some calculations. Later, they engaged in the 3-D_rep actions, in which they modelled in the 3-D mode. In the 3-DS session, the architects used the sketching pad (Group Board) during the first 10 minutes and then they stayed in the 3-D modelling mode for the remaining time. In the 3-D session, in which the designers were not given a computer-based 2-D drawing tool, the designers used the given design brief to make notes.

4.6. Shared activities to create external design representations

The duration percentages of the collaboration mode are shown in Figure 10. In the baseline study, the designers were always engaged in the meeting mode, as shown in Figure 10a. In the RS session, there was a small percentage of the duration in which the designers engaged with a different part of the design representation. This happened when the designers engaged with a different part of

Figure 9. The representation mode action over time. FTF = baseline study; RS = remote sketching; 3D = 3D virtual world; 3DS = 3D virtual world with sketching.
the workspace: exploring the drawing tools for designing and trying different pen thickness, as well as when they were reading the design brief, etc. In the 3-D session, there was an increase in the duration percentages of the individual mode actions. In the 3-DS session, there was a drop in the duration percentages of the meeting mode action and the percentage of the individual mode action was high, as shown in Figure 10c. This shows that the designers tended to work in the individual mode in the 3-D virtual worlds, compared to the baseline study. Thus, it can be said that the 3-D virtual worlds encouraged the designers to work on separate parts of the design representations.

5. Discussion

The analyses of the protocol data show that designing in virtual environments has an impact on the designers’ activities on the representation that can be categorised into two different ways: (1) the effects of the type of external design representation; (2) the effects of being in remote locations.

5.1. The changes based on the design representation: sketching and 3-D modelling

First, the results of the analysis show that the realisation actions are different between sketching and 3-D modelling. Based on the analysis of the visual design protocols, it was concluded that the two sketching sessions show a similar trend, that the realisation actions of the design representation are based on the ‘create’ and the ‘write’ actions. In the sketching, they first listed the programme components and constantly sketched new depictions using translucent paper or using the shared whiteboard. In contrast, in 3-D modelling environments, the realisation actions of the design model were based on the ‘continue’ action. This is due to the nature of modelling in 3-D virtual worlds: one mouse click creates the basic object and then the designers need to manipulate the object’s properties to make other things. This also consisted of a cycle of actions such as move/rotate/transfer/group, etc., as pointed out by Maher et al. (2005b). Thus, this ‘continue’ action consists of a series of actions that require continuing attention on the particular object. That might be one of the reasons for having longer attention spans in the 3-D virtual worlds.
Second, the results of the analysis show that the collaboration mode is different between sketching and 3-D modelling. The results suggest that the type of representation has an impact on designers’ shared activities on the design representation. In the 3-D virtual worlds, the designers worked separately on their individual parts of the design model most of the time and they came together to assist each other in the development of the design representation. In contrast, in the sketching sessions, both remote and co-located, the designers worked on the same design representation and developed the drawing together.

The reason behind the different shared activities might be: (1) in the sketching sessions, the designers had the same design representation in front of them, which might encourage them to work together all the time, and there is no personal workspace; (2) in the 3-D modelling, the design representation was a shared model but not a shared view, whereby the designers could fly over and walk around the 3-D model and they could have a personal viewpoint and workspace.

Object creation and manipulation have certain features in different 3-D virtual world platforms. In Active Worlds, the designers could only manipulate/rotate/change the properties of their own object. In Second Life, there is multiple ownership, but only one user can manipulate an object’s properties/location at a time. Thus, these features of the 3-D modelling environments might encourage the designers to work individually on separate parts of the design model. This result shows that the 3-D virtual worlds promote individual modelling, and sketching supports the shared creation of the design drawings.

5.2. The change based on the designers’ location: co-located and remote

By comparing the face to face sketching with remote sketching, one can focus on the differences between co-located and remote collaborative designing. The realisation actions in remote sketching show that more time was spent creating and deleting in remote sketching, and relatively more time was spent writing in face to face. Similarly, more time was spent modelling in remote sketching and less time was spent on decision processes. These results, although varying in magnitude, are true also of the 3-D and 3-DS remote environment. Working on the design representation is a spontaneous activity in co-located sketching and is characterised by short and frequent shifts in attention. In the remote sketching environment, the designers were using digital tools for designing and had to acquire certain knowledge and skills to create and modify the external representation. The activities in the remote sketching took longer but also allowed the designers to select pen thickness and colour. In this study, the effect of being remotely located is influenced by a change in the tools for sketching and therefore cannot be conclusive about the impact of being remotely located on collaborative design behaviour without also considering the effect of digital tools for developing the shared external representation.

5.3. The role of shared visual working space in collaborative design

The current findings suggest that the shared working space has an impact on designers’ shared activities. The shared visual space includes the communication channel, and the 2-D–3-D visual information that allows designers to work together on the design representation. These 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 remote virtual environments, rather than seeing each other’s face on the video screen. Thus, they closed the video channel window for enlarging their working space.

Most 2-D-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, Group Board, also supports the WYSIWIS approach, except that the users have the ability to configure their user interface to best suit their working needs. In contrast, 3-D virtual worlds that can be considered as shared 3-D interfaces provide a shared 3-D space and all the users have a different viewpoint, which is not analogous to the use of WYSIWIS interfaces.

The results of the protocol analysis show that this dynamic interface of the 3-D virtual worlds encourages the designers to work in the individual mode. When the designers have the same view on the design representation, they work in the meeting mode. When the designers have a shared model but not the shared view, which they have in the 3-D virtual worlds, the environment allows the designers to easily move between meeting mode and individual work. Having their own viewpoint and workspace in the collaborative virtual environments have an effect on designers’ shared activities to create external design representation, as it allows them to develop and coordinate their individual work even though they are working at the same time and on the same model.

6. Summary

The aim of this research is to examine the impact of virtual environments on designers’ interactions with the representation during a collaborative design activity through a protocol study of a pair of expert architects’ collaboration in four design tasks. The pair’s collaboration in co-located sketching was the baseline and this has been compared with three remote design sessions. The designers’ verbal and visual design protocols have been collected and analysed. The results show that the changes in the design behaviour can be categorised in two different ways:

(1) The effect of being remotely located: While remotely located there was more discussion of how to make and model the shared representation, and the duration of each action was longer even though the total time for the collaborative sessions was the same. While remotely located in a 3-D virtual world, the designers were able to move from meeting mode to individual work mode, while still coordinating with their collaborator. The effect of facilitating individual work during a collaborative session is that the designers were able to change different parts of the design model at the same time. The collaborative process is more complex than these two modes suggest and additional studies in this area will highlight the impact of different collaboration technologies.

(2) The effect of the type of external representations: When sketching, the designers did more ‘create’ and ‘write’ actions and when 3-D modelling the designers did more ‘continue’ actions, which provided more detail in the co-created representation. The effect of facilitating more detailed digital representations is that the result of the remote 3-D design sessions was a more developed design solution.
Considering these differences, the research provides knowledge of the implications of the differences in 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 study has participated in this endeavour by bringing together theories and constructs from the diverse framework of design theory, computer-supported collaborative design, visual reasoning 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 new developments in communication and information technologies, the trend is towards using these tools for communication and designing, which 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 interaction with the design representation. The knowledge provided here could be useful for system developers and designers. For example, the affordances provided in tools for 3-D modelling focus the attention of the designer on editing actions and therefore they use fewer create actions when compared to sketching. 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.

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