# IMPACT OF COLLABORATIVE VIRTUAL ENVIRONMENTS ON DESIGN BEHAVIOUR

MARY LOU MAHER, ZAFER BILDA, LEMAN FIGEN GÜL
*The University of Sydney, Australia*

**Abstract:** A collaborative design environment makes assumptions about how the designers communicate and represent their design ideas. These assumptions, including the availability of sketching, 3D modelling, and walking around virtual worlds with avatars, effectively make some actions easier and others more difficult. An analysis of design behaviour in different virtual environments can highlight the impact and benefits of the different tools/environments and their assumptions. This paper reports on a study of three pairs of designers collaborating on design tasks of similar complexity using a different design environment for each task: face to face sketching, remote sketching, and 3D virtual world. Comparing the behaviour patterns and design actions we conclude that characteristics of the design process are quite different in sketching and 3D world environments. While sketching, the architects more frequently moved between the problem and solution spaces, dealing with analysis and synthesis of ideas. The same architects focused on synthesis of the objects, visually analysing the representation, and managing the tasks to model the design when they were in the 3D virtual world.

## 1. Introduction

Recent developments in networked 3D virtual worlds and the proliferation of high bandwidth communications technology have the potential to transform the nature of distance collaboration in professional design. There have been numerous developments in systems that support collaboration that have resulted in system architectures to support information sharing and remote communication. While these initiatives have led to important advances in the enabling technologies required to support changes in global economic practices, there remains a gap in our understanding of the impact of the technologies on the working practices of the people who are the primary users of such systems.

Research into the characteristics of collaborative design can assist in our understanding of how the collaborative design process can be supported and

how new technologies can be introduced into the workplace. An understanding of collaborative design includes such factors as the role that communication media play, the use of physical materials and computer tools, and the way people communicate verbally and non verbally (Munkvold 2003). Protocol analysis has been accepted as a prevailing research technique allowing elucidation of design processes in designing (Cross et al. 1996). While earlier studies dealt mainly with protocols' verbal aspects (Akın 1986), later studies acknowledge the importance of design drawing (Akın and Lin 1995), associating it with design thinking which can be interpreted through verbal descriptions (Suwa and Tversky 1997; Suwa et al. 1998; Stempfle and Schaub 2002). By gathering information on how designers talk about and represent their design ideas during collaborative design while using different environments, we can understand how the characteristics of the different environments impact their focus during the design session.

## 2. Studying Team Collaboration

In order to understand the potential impact of high bandwidth environments on collaborative design, we first need to have data that characterizes collaborative design activity without the high bandwidth environment, i.e. face to face designing. We assume that the change in collaborative technologies should be incremental; moving from the technology already in use (usually sharing the drawings over the internet) to the use of a high bandwidth virtual environment. With these ideas in mind, an experimental study with 3 design settings was developed in order to study the impact of high bandwidth environments on design collaboration:

1. A collaborative design process in which designers work face to face with pen and paper.
2. A collaborative design process in which designers use a remote sketching system with synchronous voice and video conference.
3. A collaborative design process in which a 3D virtual world is used with synchronous voice and video conference.

We collected video and verbal protocol data in these three phases. Then we coded the behaviours we observed in the videos as well as the verbal communication. We analysed the codes and compared the collaborative activity in the three different settings, so that we could determine the impact of the change in collaborative technology. This paper presents the analysis of the data; comparing three pairs of architects' collaborative design processes in the three design environments: face to face sketching, remote sketching and 3D virtual worlds. The first collaborative environment represents the traditional way of designing, sketching, the second environment was selected as representative of the current low-bandwidth

technology (Group Board) and the third environment is a prototype of high-bandwidth technology (Active Worlds). The paper begins with a summary of the experiment design and then data collection methods. Finally, video and verbal protocol analysis of the design sessions and the results are presented.

## 3. Experiment

In our experiment, we studied pairs of designers collaborating on three different design tasks of similar complexity using a different setting for each task. We anticipate that the comparison of the same designers in three different environments would provide a better indication of the impact of the environment than using different designers and the same design task. Our designers are architects, so the design task is the design of a small building on a given site. We used the same site for each task, but specified a different type of building (gallery, library, and hostel) for each design task. This allowed the designers to become familiar with the site and to focus on the design of the building.

### 3.1 EXPERIMENTAL SET UP

Figure 1 shows the face to face session of the experiment where the designers are provided drawing materials (pen –paper), brief and a collage of the photos showing the existing building on the site and the neighbouring buildings.

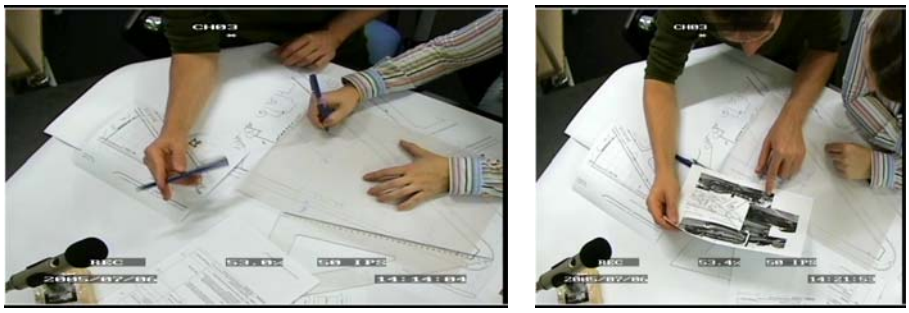
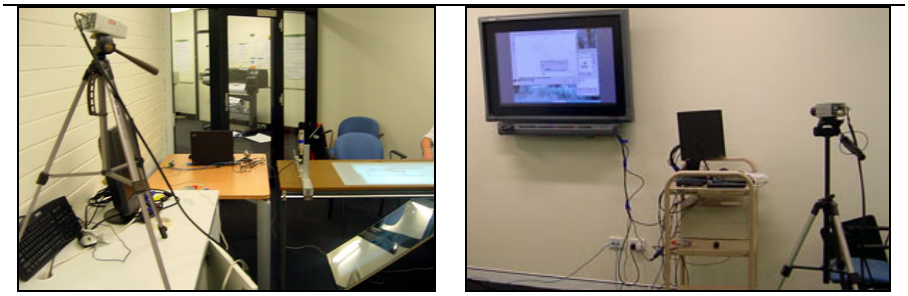


*Figure 1.* Face to face session

Figure 2 shows the set-up for the shared drawing board environment. In order to simulate high bandwidth audio and video, both designers are in the same room and can talk to each other, but can only see each other via a web cam. The set up for designer 1 is shown in Figure 2a and the set up for designer 2 is shown in Figure 2b. The location of the cameras was an important issue, since we wanted to monitor the designers' movements, verbalizations, gestures and drawing actions. Cameras 1 and 2 capture the

gestures, general actions such as walking, looking at, moving to the side, while the direct connections to the computers/screens capture the drawing process. In this setting of the experiment, the designers used Group Board, as shown in Figure 3. One designer used a pen interface (Mimio) on a projection table, shown in Figure 2a. The other designer used a pen interface on a Smart Board, shown in Figure 2b.



(a) (b)

*Figure 2.* (a) Camera 1, Desktop screen 1, and Mimio on workbench; (b) Camera 2, desktop screen 2, and Smart Board

In the third setting of the experiment, the designers used an extended 3D virtual world application in Active Worlds, shown in Figure 4. The 3D world includes a multi-user 3D building environment, video contact, a shared whiteboard, and an object viewer/insert feature. Again, the designers are in the same room with a similar camera set up. While the shared whiteboard was available in the third setting, the designers were only trained to use the 3D world.


*Figure 3*. Group Board interface

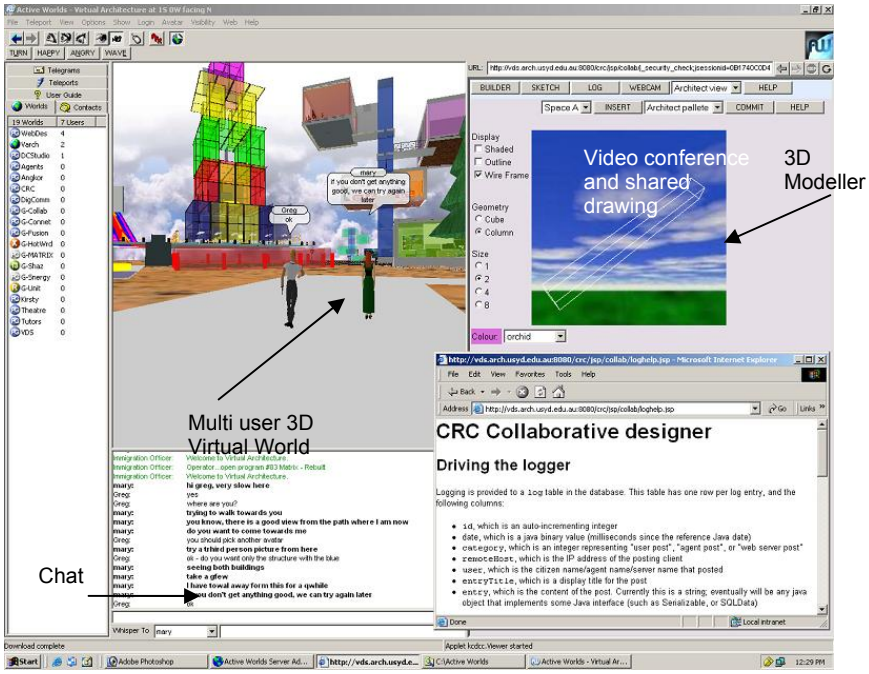



*Figure 4.* Extended virtual world

## 3.2 EXPERIMENTAL PROCEDURE

The experimental procedure was:

1. The designers were given a design brief and a collage of the photos of the site they are required to build on. They were given time to read through the design brief and inspect the site layout and photos. They were given paper and pencils and were asked to complete their design session in 30 minutes.

2. The designers were presented a short description of how they could use the Smart Board and the Mimio Tool: both are pen and digital ink interfaces. The Smart Board is attached to a vertical plasma display and the Mimio is placed on a horizontal projection display (Figure 2).

3. The designers were given a 15 minute training session on the use of Group Board. In the training session participants were engaged in doing a tutorial in order to review and/or build their skills in using specific features of the application provided for collaboration.

4. The designers were given a new design brief and a collage of the photos of the same site. The site layout was set in the share whiteboard application as a background image on several pages so that the designers can

sketch on them. They were asked to complete their design session in 30 minutes.

5. After a 5 minute break, the designers were given a 30 minute training session on the use of extended 3D virtual world. Similar to the previous training session, they were asked to do a tutorial in order to review and/or build their skills in using specific features of the software application.

6. The designers were given a new design brief and a collage of the photos of the same site. This time the designers were using the extended 3D virtual world. They were asked to complete their design session in 30 minutes.

### 3.3 VIDEO AND VERBAL DATA CODING

The data from the experiments comprises 3 continuous streams of video and audio data for each pair of designers. In this paper we report on the analysis and interpretation of three pairs of designers. The stream of data for each session is segmented for coding and analysis. We used the software INTERACT[1] for our coding and analysis process. More information on the reasons for choosing this software and how it improved our coding process can be found in (Candy et al 2004).

Our segmentation is based on an interpretation of an event. In the study done by Dwarakanath and Blessing (1996), an event is defined as a time interval which begins when a new portion of information is mentioned or discussed, and ends when another new portion of information is raised. This event definition is an optimal one for our study as well, since the occurrences of actions and intentions change spontaneously as architects draw and communicate interactively.

An event can change when a different person starts speaking in a collaborative activity if s/he is introducing a new portion of information. In some cases the conversation goes on between the actors however the intention or subject of interest remains the same. In this paper we refer to the designers as Alex and Casey. For example, in Segment 48 both Casey and Alex take turns in one segment, however their subject of interest is still the "ramp to a car park":

*Segment 48*:

"Casey: This is... there is a photo of there. That is actually a ramp to a car park. And then there is a building and a little <inaudible>

Alex: And that is the ramp?

Casey: That is the ramp."

[1] www.mangold.de

*3.3.1. Coding Scheme*

Each segment is then coded according to a coding scheme. The coding scheme allows us to compare and measure the differences in the three design sessions. We used 4 categories of coding schemes: communication content, operations on external representations, design process and working modes.

The communication content category is applied to the transcribed conversation between the two designers, and one code is assigned to each segment. This code category has 5 codes as shown in Table 1. The communication on software features includes questions about how to do specific tasks with the software, talking about individual experience of how to do things, problems faced during the use of the software, any feedback about the interface or use of software /statements of frustration about not getting something right.

TABLE 1. Coding Scheme

| | |
|---|---|
| **Communication Content** | |
| Software features | Software/ application features or how to use that feature |
| Designing | Conversations on concept development, design exploration, analysis-synthesis-evaluation. |
| Awareness | Awareness of presence or actions of the other |
| Reps | Communicating a drawing/object to the other person |
| Context free | Conversations not related to the task |
| **Operations on External Representations** | |
| Create | Create a design element |
| Modify | Change object properties or transform |
| Move | Orientate/Rotate/ Move element |
| Erase | Erase or delete a design element |
| InspectBrief | Looking at, referring to the design brief |
| InspectReps | Looking at, attending to, referring to the representation |
| **Design Process** | |
| Propose | Propose a new idea/concept/ design solution |
| Clarify | Clarify meaning or a design problem, expand on a concept |
| AnSoln | Analyse a proposed design solution |
| AnReps | Analyse/ understand a design representation |
| AnProb | Analyse the problem space |
| Identify | Identify or describe constraints/ violations |

| | |
|---|---|
| Evaluate | Evaluate a (design) solution |
| SetUpGoal | Setting up a goal, planning the design actions. |
| Question | Question / mention a design issue |
| **Working Mode** | |
| Meeting | Working together on the same design/artefact |
| Individual | Working individually on a different part/aspect of the design |

The operations on external representations category looks specifically at the actions the designers perform while using the environment (Table 1). Each segment is interpreted using the video of the designers' behaviour including movements or gestures, and the video stream of the computer display showing how the software was being used. Inspecting representations need further explanation because the action refers to different behaviour in 2D and 3D environments. Inspect representation in Group Board may refer to:

Looking at the representation and referring to its parts/aspect

Using hand gestures over the representation

Attending to a visual feature of the representation

Zooming in and out

Scanning

Inspect representation in 3D world may refer to:

Looking at the model and referring to a design object.

Using hand gestures over the representation

Attending to a visual feature in the environment

Navigating or changing the view point in the environment

The design process category characterizes the kinds of design tasks the designers are engaged in for each segment (Table 1). Assigning a design process category takes into consideration the words spoken during each segment. The codes in the design process category are an adaptation of the coding scheme developed by Gero and McNeill (1998).

In developing the working modes category we took a similar approach to Kvan (2000) where he defined collaborative designing as a "closely coupled" process or a "loosely coupled" process. In a closely coupled process, designers work together on the same artefacts simultaneously while in a loosely coupled process, design participants work with different artefacts at a different or the same time. In this category "meeting" code refers to designers working together on the same design/artefact, and "individual" code refers to designers working individually on a different part/aspect of the design.

*3.3.2. Combined codes*

We combined some of the external representation codes and the design process codes into generic activity components in order to highlight observed different behaviours in the different environments. Create and Change activities represent the summary of operations on external representations. The design process codes are combined into four generic activities that are analyse, synthesize, manage task and visual analysis. By using combined codes we can more easily see the changes between the three design environments without getting lost in patterns of multiple codes. A summary of the combined codes is shown in Table 2.

TABLE 2. Combined Codes

| **Combined Codes** | **Individual Codes** |
|---|---|
| Create | Create |
| Change | Move, Modify |
| Analyse | Analyse problem, Clarify, Identify |
| Synthesize | Propose, Analyse solution |
| Visual Analysis | Analyse representation, Evaluation |
| Manage Tasks | Set up goal, Question |

*Create _Change*

The 'create' operation in the FTF sketching environment was usually associated with drawing actions such as drawing a line, a complete or an incomplete shape, making symbols etc. Create action in Group Board sessions involved using drawing tools that are line, shape, fill etc. which is again similar to the FTF sketching. However Create action in the 3D world is usually just a click on an existing object, so that it is duplicated. Because the designers duplicate/create building blocks of space boxes, walls or columns, the building elements are created once and then re-arranged, by moving or modifying them. In our previous studies create - move - modify operations were observed to follow each other many times in the 3D virtual world and this pattern was associated to "making the model" (Maher et al. 2005a,b).

Move (carrying an object to another position) and Modify (changing its properties) actions are related to either Group Board or 3D World environments. We combined move and modify actions under one name "Change", referring to the change in location or change of property of the entity or object.

*Analyse_ Synthesize*
We focused on two main activities that are related to the development of the design ideas at an abstract level. Analyze activity is assumed to take place in the problem space, and Synthesize activity is assumed to take place in the solution space. Analyze activity includes the following codes in the coding scheme: analyze problem, clarify, and identify. Synthesize activity includes the following codes: propose and analyze the design solution.

In protocol studies, analyze-synthesize activity refers to a design thinking cycle which involves analyzing a problem, proposing a (tentative) solution, analyzing the solution and finally evaluating it (Gero and McNeill, 1998). A similar cyclic process was emphasized in creative cognition literature as explore-generate-evaluate actions (Finke et al., 1992). However in many cases, it is only after designers synthesize a solution that they are able to detect and understand important issues and requirements of the given problem. Lawson (1990) called this phenomenon 'analysis through synthesis". The analysis of tentative solutions has been defined as a kind of design thinking and an expected behavior during the conceptual phase of designing.

*Visual Analysis*
Visual analysis activity is based on constructing a specific representation, thus the activity is different from analysis of the problem or the solution space. Analysis-synthesis refers to idea and design solution development via constructing an external representation. Visual analysis is purely dependent on the representation; judgments of what it should look like, how elements come together, designers' preferences on constructing it, and so on. Visual analysis involves seeing or imagining what the object looks like in 3D, so the "analyze representation" code is included in this activity. The evaluate code is included in this combined code as well because we observed that evaluation was mostly based on visual analysis.

*Manage Tasks*
Managing tasks refer to planning design actions ahead and leading the collaboration partner towards the goals to make the design. Questioning each other about design issues or knowledge is also involved in this activity. Manage tasks include the following codes from the coding scheme: Setting up a goal and questioning.

## 4. Interpretation and Discussion of Results

After coding each segment, the coding software INTERACT provides us with the total duration of each action in each category as well as how much time each participant spent on each action. The duration of each action is

divided by the total elapsed time for each session (which is 30 minutes for each session). This gives us the duration percentages for each action or action category. Table 3 shows duration percentages of the three action categories from the coding scheme. These are the averaged values of the three architect pairs collaborating in the three different design environments. Table 3 shows that around 72 percent of the total time is spent on collaborative communication in face to face sketching, Group Board and 3D world session. Thus the amount of communication is nearly the same in the three environments. The architect pairs spent 92-97 percent of the total design session time on operations related to external representations. Again the time spent on dealing with external representations does not seem to be significantly different over the three different design environments. However there is more variance between duration percentages of the design process actions category. In face to face sketching (FTF) session, architects spent 70 percent of their time on design process actions, however in 3D World session they spent 40 percent and in the Group Board (GB) session, 50 percent of the total time is spent on design process actions.

TABLE 3. Duration of action categories as a percentage of the total elapsed time

| | FTF | Group Board | 3D World |
|---|---|---|---|
| Communication content | 72% | 73% | 72% |
| Operations related to external representations | 94% | 92% | 97% |
| Design process | 69% | 50% | 41% |

We tested if there are significant differences between the pairs in terms of their design behaviour (coded activity categories). The ANOVA test (ANOVA with replication, $P<0.05$) results show that there is no significant difference between the pairs' communication content ($p=0.58$), their operations related to external representations ($p=0.91$) or their working mode. This result supports that the architect pairs were similar in level of knowledge and experience, and their collaborative behaviour did not show a significant variance amongst the different pairs. Note that only design process is significantly different ($p=0.0015$) between the pairs. This result is not surprising since the design activity of one person might change due to the situations involved in the current context, and the variance in individual design strategies could have an effect on the collaborative design process.

It was also observed that the amount of time spent on communication in the three design sessions was very similar (Table 2); however the content of communication varied amongst the face to face sketching, remote sketching and 3D modelling environments. When we compared the communication content in the 3 environments, one significant difference was the amount of

communication about designing. This includes the design process related actions in our coding scheme, which could be interpreted as the actions needed for developing ideas/concepts and reasoning about them to reach a design solution. The ratio of talking about designing decreases from FTF to 3D world session, however percentages of other communication content categories increase. Figure 5 shows that the architects spent more time on the representation related context in the 3D virtual world. This involves talking about which elements they could use to represent their design ideas or what the representation looked like in the environment. The architects focused on the "representation" more in the 3D virtual world because they had to concretize their design ideas immediately, however in the sketching environment the representation could remain abstract.

Talking about software features occurred only in the digital media as expected, as well as the communication on awareness. Awareness percentages were higher in the 3D world. The discussion on awareness of others is due to the significance of the information about the other designer's location in the 3D virtual world and their actions with respect to the design model they are creating.

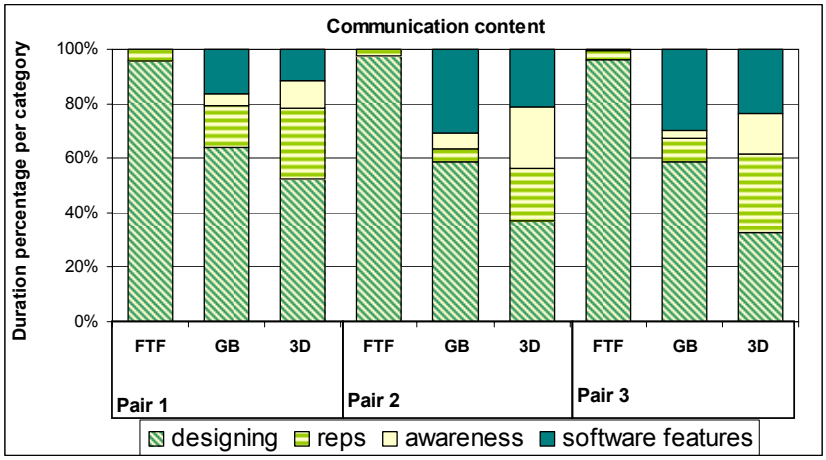



*Figure 5.* Communication content in face to face (FTF), Group Board (GB) and 3D World (3D) sessions for each pair.

Figure 6 shows the time spent on create and change activities which changed over the three environments. When we compare the Create and Change activities, one significant difference is that "Change" occurs in the remote/digital media, and the time spent on change activity is highest in the 3D world environment in all cases. Consequently Create activity has the smallest percentage in the 3D world, since the designers used the same objects by duplicating and moving them around. Thus the nature of the 3D modelling is not based on creating new things, as in the sketching

environments, where designers draw and trace over and re-draw the same things instead of copying them or moving them around.

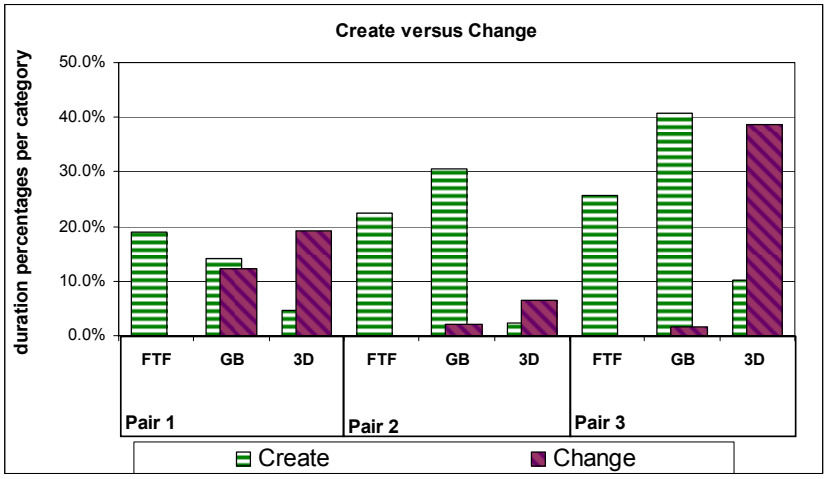



*Figure 6.* Occurrence of "Create" and "Change" activities in face to face (FTF), Group Board (GB) and 3D World (3D) sessions for each pair.

Operations on external representation category codes are shown along the timeline of the sessions in Figure 7. The beginning of the session is on the left, and the length of each horizontal bar indicates how long the designer spent on each operation. Each designer's external operations are coded separately indicated by the numbers 1 and 2. Figure 7 demonstrates Pair 3's external operations patterns visually in order to exemplify how we reached our conclusions about the action cycles. It can be observed in pair 3's actions chart that the FTF and remote sketching sessions have similar patterns in the operations on external representation and the 3D virtual world looks very different. In the FTF and remote sketching sessions the "inspect representation" was followed by "create" many times along the timeline (Figure 7a, 7b). In the 3D virtual world the "inspect representation" was still followed by "create" and additionally followed by "move" and "modify" many times along the timeline of the session (Figure 7c). This demonstrates the relative richness of the 3D virtual world for manipulating the external representation.

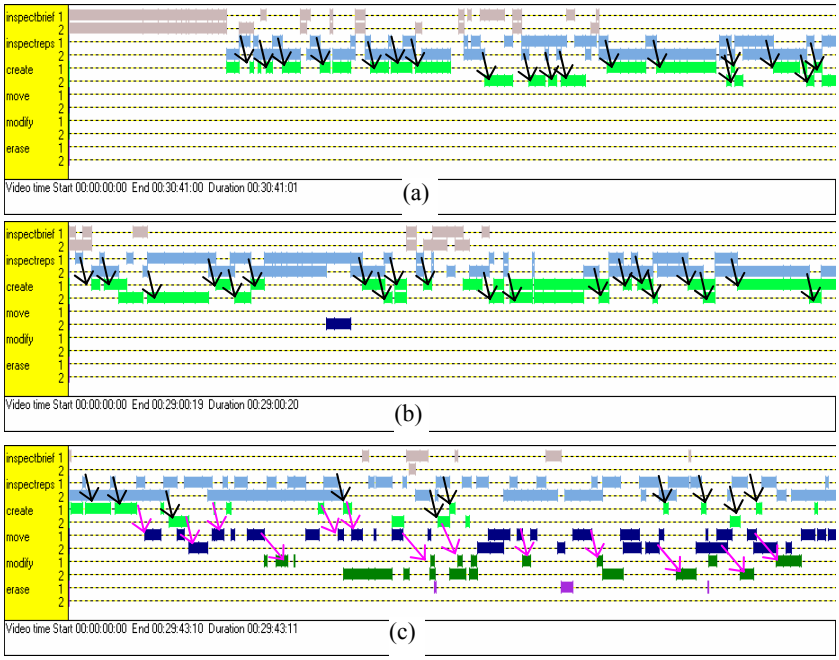



*Figure 7.* External operations of pair 3 in (a) Face to Face, (b) Group Board, (c) 3D World session.

Figure 8 shows the duration percentages of Analyse-Synthesize activity of the three pairs separately over the three design sessions. The graph demonstrates that there is a drop in the duration of the analysis-synthesis activities across the three design environments, FTF showing the highest percentages.

Figure 9 shows times spent on 'manage task' and 'visual analysis' activities in percentages. The graphs show that there is a significant increase in the duration of these design activities across the three design environments, 3D virtual world showing the highest percentages (Figure 9a, 9b).

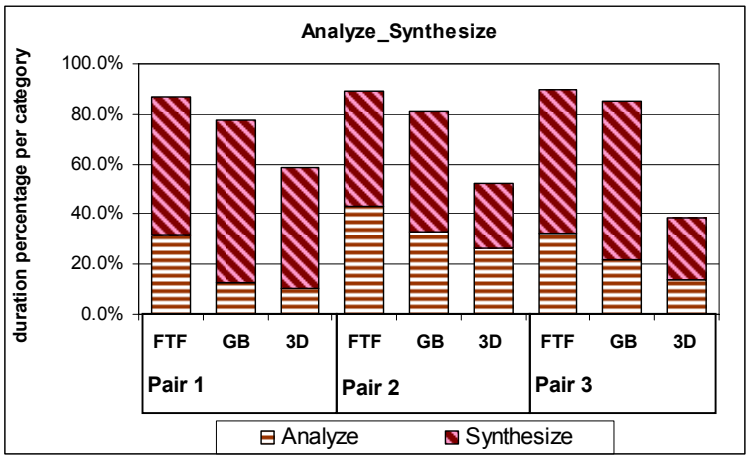
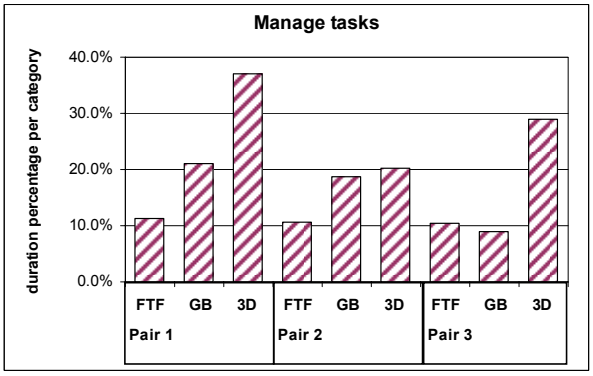
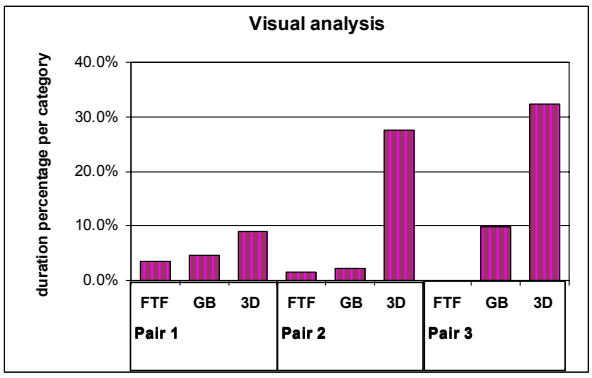



*Figure 8.* Analyse-Synthesize activity in FTF, GB and 3D World sessions for each pair




(a)




(b)

*Figure 9.*(a) Manage task (b) Visual analysis activities in FTF, GB and 3D World sessions for each pair

A summary of our analysis of the working modes category is shown in Figure 10. When the designers were working face to face, they were always engaged in "meeting" mode, during which they were communicating and acting on the same aspect of the design. When the designers were working remotely, there was a small percentage of the time during which they were working on their own, focusing on different aspects of the design. For the three architect pairs' sessions analysed, the percentage of meeting working mode is highest for face to face and remote sketching sessions while the percentage of individual working mode is negligible. However in the 3D world, architects worked less in meeting mode and relatively more in individual mode. This difference could be due to the nature of the 3D modelling environment, where participants have the opportunity to do task division and work separately (individual mode) on different aspects/parts of the design to be built. This result also shows that the 3D virtual world could support teams to work collaboratively but at the same time could support individuals to work separately in the different part/aspect of the design.

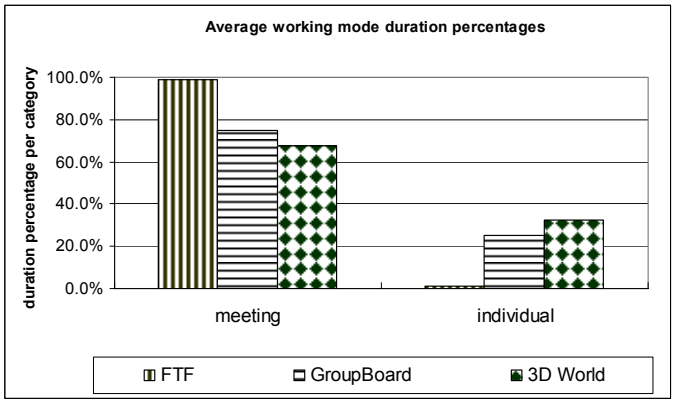



*Figure 10.* Bar charts for working mode of designers (average of 3 pairs over the 3 design phases)

## 5. Conclusions

As available bandwidth increases and new virtual environments are developed to support collaborative design, designers are provided with a broader range of choices in how they communicate and collaborate at various stages of the design process. While it is essential and expected that the basic requirements for effective verbal communication are available during the collaborative session, there are numerous options for providing a shared representation of the design problems and solutions. In this study we focused on the impact of moving from a familiar face to face sketching

representation to two kinds of remote shared representation options: sketching on a shared drawing board and modeling 3D objects in a virtual world. Our study reports on 3 pairs of designers. While this is a small sample, the designers showed similar behaviors indicating that the results at least report on the kinds of differences and impact that we can expect to occur within the larger design profession. Our analysis, at a high level, shows that designers easily adapt to new environments as seen in our overall results on similar percentages of communication and operations on external representations. The difference in the environments is the impact of remotely communicated representations as sketches or 3D objects on the focus of the designers.

The experiments described here characterize and compare the design behavior of pairs of architects using three different tools/media for designing. We demonstrate that architects developed abstract concepts, analyzed, synthesized, and evaluated them when they were sketching and the same architects focused on synthesis and visual analysis of the objects and the making of the design, when they were in the 3D virtual world. Designers, while using the 3D virtual world and remote sketching, were able to move and change the objects and entities of their designs, allowing them to focus on iterations of the design solution. This is in comparison to face to face sketching in which a change meant redrawing the design representation. We also observed that the designers in the 3D virtual world spent relatively less time synthesizing design solutions when compared to sketching, indicating that the focus was on the design being modeled rather than generating numerous alternatives.

In conclusion, our studies show that while designers adapt to new environments and are able to effectively design face to face or remotely, the differences in the environments focus the designers on different aspects of the design process. Ideally, a designer should have multiple ways to communicate and represent the design problems and solutions. In our next set of experiments we provide the designers with sketching and 3D modeling within the same virtual world environment to determine how and when each is used when given the choice.

## References

Akın, Ö: 1986, *Psychology of Architectural Design*, Pion, London.

Akın, Ö and Lin CC: 1995, Design protocol data and novel design decision, *Design Studies*, **16**: 221-236.

Candy, L, Bilda, Z, Maher, ML and Gero, JS: 2004, Evaluating software support for video data capture and analysis in collaborative design studies *in Proceedings of QualIT04 Conference,* Brisbane, Australia (CD-Rom no page numbers).

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

Dwarakanath, S, and Blessing, L: 1996, The design process ingredients: A comparison between group and individual work, *in* N. Cross, H. Christiaans, and K. Doorst (eds) *Analysing Design Activity*, John Wiley and Sons, Chicester, West Sussex.

Finke RA, Ward, TB & Smith, SM: 1992, *Creative Cognition: Theory, Research and Application*, MIT Press, Cambridge, MA.

Gero, JS and McNeill, TM: 1998, An approach to the analysis of design protocols, *Design Studies* **19**: 21-61.

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

Lawson, B: 1990, *How Designers Think*, London, Boston, Butterworth Architecture.

Maher, ML, Bilda, Z and Marchant, D: 2005a, Comparing collaborative design behaviour in remote sketching and 3D virtual worlds, *in Proceedings of International Workshop on Human Behaviour in Designing,* Melbourne, Victoria, Australia, Key Centre of Design Computing and Cognition, University of Sydney, pp. 3-26.

Maher, ML, Bilda, Z, Gül, LF and Marchant, D: 2005b, Studying design collaboration in virtual worlds, *in* Gero, JS and Bonnardel, N (eds) *Studying Designers'05*, Key Centre of Design Computing and Cognition, University of Sydney.

Munkvold, BE: 2003, *Implementing Collaboration Technologies in Industry: Case Examples and Lessons Learned*, Springer-Verlag, London Ltd.

Stempfle, J and Badke-Schaub P: 2002, Thinking in design teams- an analysis of team communication, *Design Studies* **23**: 473–496.

Suwa, M and Tversky, B: 1997, What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies* **18**(4): 385-403.

Suwa, M, Purcell, T and Gero, JS: 1998, Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions, *Design Studies* **19**(4): 455-483.