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UNDERSTANDING DESIGN COLLABORATION: COMPARING FACE-TO-FACE SKETCHING TO DESIGNING IN VIRTUAL ENVIRONMENTS

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ABSTRACT:

Recent developments in communication and information technology offer new collaborative design environments to designers. Designing and collaboration has been changing with the introduction of these new design environments. We conducted a series of experiments to identify similarities and differences between co-located design and remotely located design sessions in order to have a better understanding of the impact of different virtual environments on design collaboration. Our results show that the changes in the design behaviour can be categorised in two different ways: (1) the effect of being in the same location and (2) the effect of the type of external representations.

Keywords: Collaborative design, protocol analysis, sketching and 3D modelling

1. INTRODUCTION

The developments in and the extensive use of internet technologies have brought about fundamental changes in the way **A**rchitecture, **E**ngineering and **C**onstruction (AEC) professionals collaborate and design. This change has been partly to improve efficiency, and also because of the global nature of the industry and the pressure for communication and collaboration between AEC professionals using various computer-mediated technologies. Thus, the 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 **C**omputer **S**upported **C**ollaborative **W**ork (CSCW) systems. Although these developments 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 design collaboration and how different types of communication might change design collaboration and how different types of digital design media affect architects' interaction with the design representation.

The aim of the study is to identify similarities and differences in collaborative design behaviour in different virtual environments, in order to acquire a better understanding of the impact of different virtual environments on design collaboration. 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 (Hennessy and Murphy, 1999; Seitamaa-Hakkarainen et al., 2000). Collaborative design activity requires the participation of individuals for sharing information and organising design task and resources (Chiu, 2002). Our research mainly focuses on the verbal and visual design externalisations in a collaborative design context, based on the assumption that interaction between team members requires effective communication through discourse and visual representations in the design environments. The study includes two aspects (1) understanding the collaborative design process and (2) designer's interaction with an external design representation.

2. STUDYING DESIGN COLLABORATION

The first aspect of the study deals with the processes of design collaboration. Kvan et al. (1997) pointed out that as collaborators come together in design, the nature of their activity does not change, since collaboration still requires a designer to attend to design as individual tasks, as well as collaborating. He developed a model of design collaboration that includes three joint decision phases (meta-planning, negotiation and evaluation) and an individual work phase (Kvan et al. 1997). In this model, these phases have been iterated until designers come up with a satisfied design solution. Based on this view, we consider that understanding collaborative design activity requires understanding an individual's design activity and how external representations are created and shared amongst participants.

The second aspect of the study involves the interaction with the external design representation. In design research, external design representations (sketches, models, diagrams) are recognized as having important roles in the design process (Schön, 1983; Ak•n and Lin, 1995; Goldschmidt, 1991; Goldschmidt, 1994). In particular, sketches comprise possible design solutions and also seem to be essential for recognizing conflicts and possibilities (Ak•n and Lin, 1995) as well as for revising and refining ideas, generating concepts and facilitating problem solving (Do et al., 2000). Designers sketching in the early stages of a design process and the role of sketching in designing have been examined (Ak•n and Lin, 1995; Goldschmidt, 1991; Schön and Wiggins, 1992; Goel, 1995; Suwa and Tversky, 1997), showing the different roles sketches play in visuo-spatial reasoning and their connection to different aspects of the design process.

2.1. METHOD

Based on these views in the literature, to investigate the impact of technology on design collaboration a series of experiments were conducted[1]. In order to understand the changes in designers' behaviour, there is a need to have baseline data that characterises collaborative design activity without the technology, that is, co-located sketching. Then there is a need to gather the verbal and visual data to characterise and identify the changes that occur in design

[1] 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) (CRC study). The results of this research have been published in several conferences (Maher et al. 2006 a,b,c). With a different research focus, this paper analyses a subset of experiment sessions of the CRC study.

collaboration when the different technologies are introduced. With these ideas in mind, the empirical data forms two groups:

- Baseline study (co-located sketching): A collaborative design process in which designers work face-to-face (FTF) with traditional materials;

- Comparison study (remote designing): A collaborative design process in which designers use three different collaborative technologies with full communication channels (video and audio); a remote sketching application (RS), a 3D virtual world (3D) and a 3D virtual world with sketching (3DS).

2.1.1. EXPERIMENTAL SET UP

- Baseline study

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

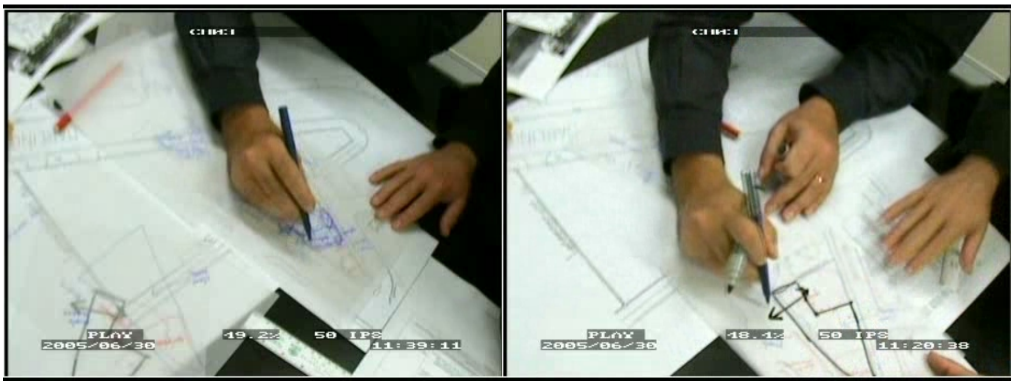

Figure 1: The baseline study, face-to-face design session

In the baseline study, two architects are collaborating on a design task in co-located (face-to-face) sketching in which they are together around a table and develop a design representation using traditional materials (pen-paper).They are asked to design a contemporary art gallery that includes permanent and temporary exhibition halls, a sculpture space, art store, services and offices. Their design actions and communications are captured in the **D**igital **V**ideo **R**ecording (DVR) system.

- Comparison study

In the comparison study, the aim is to compare three collaborative design sessions with the baseline study (FTF): (1) FTF and remote sketching (RS), (2) FTF and 3D virtual world (3D), and (3) FTF and 3D virtual world with sketching (3DS). The key objective of the study is to characterise the differences and similarities between digital media for collaborative design and traditional FTF paper sketching. Figure 2 shows the DVR views of the three experiments in which the architects are collaborating within the technology. 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 in the DVR system.

a b c

Figure 2: The Comparison study, two designers collaborating within three different collaborative virtual environments: (a) RS-Groupboard, (b) 3D-Active Worlds, (c) 3DS-DesignWorld

In the remote sketching (RS) session, the architects 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 design 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. Active Worlds offers “library-based” design. In a typical library-based design, the objects are pre-defined outside the world and are provided by the object library of the design platform. Modification of the shapes and forms of the objects require an object library update. A set of design elements (walls, slabs, space objects and columns) and navigation signs were provided at the entrance of the site.

In the 3D virtual world with sketching (3DS) session, the architects used a prototype system, DesignWorld[2] which included a 3D virtual world augmented with a number of web-based communication and design tools, as shown in Figure 2c. In the 3DS session, the architects are asked to design a shopping arcade and a tower, which includes a viewing platform, restaurants, shops, amenities and services. DesignWorld 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 Maher et al., 2005a,b; Gül and Maher, 2006a,b, for details of the experiments, training sessions and DesignWorld).

2.2. 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 design cognition studies (Cross, 2001). Purcell et al. (1996) presented three approaches to developing the structure of a coding scheme: theory based, externally derived and data generated structures. This study uses the last two approaches: externally derived and data generated. The basis for the development of the coding scheme is a consideration of the expected results of the study. The expected result of the study is that the different technologies will change the ways in which the designers collaborate, their individual design behaviour, and the ways in which they interact with the design representation. Thus, measuring the changes in (1) the collaboration design process, and (2) the interaction with the design representation are necessary.

2.2.1. COLLABORATIVE DESIGN PROCESS

The first main category, the ***collaborative design process,*** refers to verbal design protocols that have direct relevance to designers' collaboration to solve a particular design problem. The design communication category captures the discussions between the designers in terms of how they

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[2] This prototype was developed as part of the CRC CI project.

develop and generate design solutions and communicate the design ideas. The design communication category is further divided into sub-categories, as illustrated in Table 1. The awareness code looks at the discussions held between the participants that are related to each other's presence and activities. The communication technology code looks at the discussions held between participants that are related to the use of technology in collaborative environments, in terms of how to use the tools, how to manipulate objects, and their properties.

Table 1: The first level of the collaborative design process coding scheme

	DESCRIPTIONS	***Types of data***
Collaborative design process		***Verbal***
Design Communications	Looks at discussions about design, design ideas and design collaboration, semantic and scope	
Collaboration process	Looks at discussions that are related to the collaboration process: meta-planning – negotiation – individual work – evaluation (adapted from Kvan's (1997) cognitive model of collaboration)	
Design process	Looks at discussions that are related to the design idea and developing the design: problem analysis – solution moves (proposing ideas: change-progress)- clarify/restate - set up goals - synthesis	
Design semantics	Looks at discussions that are related to the semantics of the design elements: function – structure - emergent element – past knowledge	
Design scope	Looks at discussions that are related to the level of design exchanges: low-level – high level (adapted from Vera et al., 1998).	
Awareness	Looks at discussions about the presence, location and the activities of others	
Communication Technology	Looks at discussions held between participants related to the use of the tools and the collaborative environment	
Other	Looks at discussions that are not related to any of the above communication content	

2.2.2. INTERACTION WITH EXTERNAL DESIGN REPRESENTATION

The second main category, ***interaction with the design representation,*** includes the verbalisation and the visualisation of the external design representations (verbal-visual design protocols) to communicate the design ideas with her/himself and/or to others. The interaction with the design representation coding scheme captures: (1) how architects create the external design representation, (2) how they approach construction of the design representation, (3) how they use visual information and how they inspect/interact with the interface/tools, given materials and the representation, and (4) what visuo-spatial features of the representation they focus on while they are developing the design solution, as shown in Table 2.

Table 2: The first level of the interaction with the design representation coding scheme

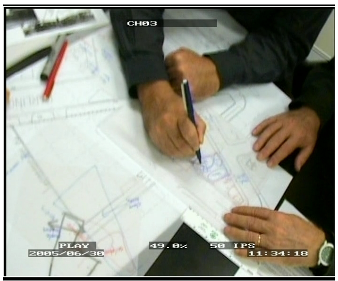
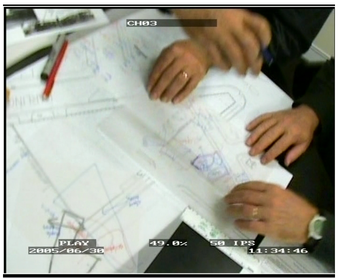
Interaction with design representation	DESCRIPTIONS	Types of data Verbal & Visual
Realisation	Looks at discussions and actions about concretisations of design ideas: (1) Realisation action: create – write – continue – delete and (2) Realisation process: modelling – describe – decision (borrowed from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

2.2.3. SEGMENTATION

During segmentation, the design protocols are divided into smaller units. The data of the study consist of a continuous stream of video and audio that has two sources, the designers 1 (Greg) and designer 2 (Lee). Since the aim of the study is to investigate the verbal and visual design externalisations of the designers in the collaborative design context, there is a need for a thorough investigation of each designer's externalisations (verbal and visual design protocols). The first segmentation consideration is similar to the single-subject think-aloud protocol method. In order to separate utterances into meaningful units, which can be coded under a specific category relating to the design processes and actions, a segmentation procedure needs to be applied. The second consideration is related to the uninterrupted flow of the communication and the content of the communication. Similar to Maher et al. (2005b) each design session is segmented twice: (1) reflecting Greg's design actions and intentions, and (2) reflecting Lee's design actions and intentions. Consequently, the two major segmentation rules, which are the utterances-based segmentation method (Gabriel, 2000; Maher et al., 2005b) and the actions-and-intentions based segmentation method (Gero and McNeill, 1998), are combined in this study.

The segments might include the combinations of visual and verbal design protocols: (1) having the verbalisations only when there is not any visual action, (2) having the visual actions only when there is not any verbalisation, and (3) having both the verbalisations and visualisations when designers talk and sketch/model at the same time in a segment. Table 3 shows one of the designers' segmentation protocol extracts, taken from the baseline study (FTF). As illustrated in Table 3, the verbal and the visual design protocols could be the spontaneous (concurrent) actions, as shown in segments 78 and 80, but sometimes there are only verbal design protocols, as shown in segment 79.

Table 3: Segmentation in the baseline study (Greg's segmentation)

Segment No.	Verbalisation	Visualisation
Segment 78	Greg: And then support spaces behind it, because you can make this deeper. Lee: Yes, correct, yes, we could just slot it in a bit and that would give us then …	[Greg is sketching] 
Segment 79	Greg: You'd have to walk through the gallery to get to other things but we can change that shape a bit.	[No action] 
Segment 80	Lee: Forty by twenty-five, so a thousand by half five hundred five hundred one two three four five. Greg: Which is a bit too much. Lee: A bit too much isn't it.	[Greg is sketching] 

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 chronological order, based on her/his understanding of the content of the segments and the coding scheme. In this study, Interact software[3] is used for the segmentation and the coding of the video sessions (see Bilda et al., 2006 for details on software support).

3. RESULTS AND DISCUSSIONS

The duration percentages of each action category are examined to measure the similarities and differences of designers' behaviour in each design session.

- Overview of the data

The attention changes/shifts are examined by an analysis of the segment durations in each of the design sessions, as shown in Table 4. Since we segmented the continuous stream of data according to a change in the verbal or visual design protocols, the numbers of segments in each session provide us with information about how frequently the changes/shifts occurred. In the baseline study (FTF), the mean (M) duration of segments is the shortest (M11.64 second) and the number of segment is the highest (182 count). On the other hand, the segment durations increased and the number of segments decreased in the virtual environments, as shown in Table 4. The longest segment durations (56.5 and 123.5 second) are observed in the 3D and the 3DS sessions, when the designers spent time elaborating on the design model. The higher standard deviation values in the comparison studies show this tendency. The segment durations for all sessions are positively skewed, as illustrated in Table 4. The high kurtosis values show that the distribution of the durations of segments is not flat. This result shows that the designers experienced more attention shifts in the baseline study (less time and more segments), and they had fewer and longer attention shifts in the virtual environments.

Table 4: Statistics on the duration of segments

Sec	FTF	RS	3D	3DS
Mean (sec)	11.64	12.15	12.84	16.25
Standard Deviation	5.55	5.73	7.76	11.21
Kurtosis	1.13	1.25	8.00	19.35
Skewness	0.82	0.99	2.25	2.95
Minimum (sec)	0.97	1.80	1.90	1.53
Maximum (sec)	36.03	31.10	56.50	123.53
Average Segment Count	182	176	168	139

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

- Collaborative Design Process Actions

The duration percentages of the first level of the collaborative design process actions are shown in Figure 3 (comparing the baseline study with the three virtual environments: FTF and RS, FTF and 3D and FTF and 3DS). The durations are divided by the total time elapsed in each session, where the duration percentages are obtained for each code. Not surprisingly, they talked about designing most of the time in the entire sessions, as illustrated in Figure 3. When the remote virtual environments were introduced to the design situation, the communication content was still mainly about designing (design Com), followed by communication about software features (Comm Tech) and the awareness actions. The discussions relating to the software features (Comm Tech) were higher in the RS session, as shown in Figure 3a, c. This is because the designers spent time on saving and uploading images constantly in Groupboard. In addition, Figure 3b shows that the awareness code is higher in the 3D session, in which the designers discussed the locations and each other's actions in the virtual worlds.

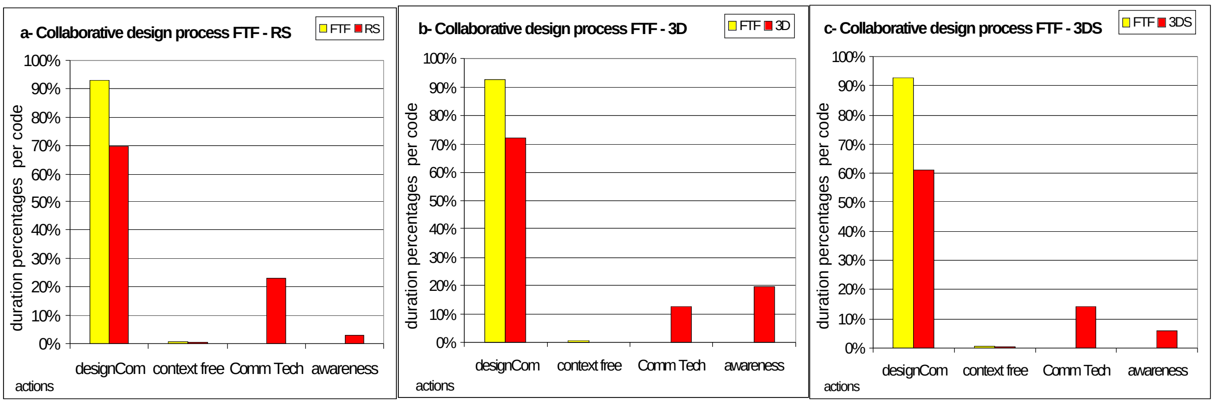


Figure 3: The duration percentages of the high level of the collaborative design process actions: (a) FTF and RS, (b) FTF and 3D and (c) FTF and 3DS

Table 5 shows the average durations of the collaboration process actions over time in all design sessions. The highest percentages are shaded as grey for each category, as shown in Table 5. In the baseline study, the duration percentages of the "negotiate" and the "evaluate" actions are higher. In the 3D session, the duration percentages of the "meta-planning" actions are higher when we compare them to those of the baseline study, as shown in Table 5. In the RS session, similar to the baseline study, "individual work" actions did not take place, representing only 0.2%. However, in the 3D and the 3DS sessions, the individual work action is observed (14.4% and 19.2%): the highest occurred in the 3DS session, shaded grey in Table 5.

Table 5: The duration percentages of the collaboration process actions

(Sec- average) -%	FTF	RS	3D	3DS
Meta-planning	(91.84) 2.6%	(194.93) 5.4%	(318.64) 8.9%	(232.03) 3.2%
Negotiate	(2982.83) 82.9%	(2178.6) 60.5%	(1643.03) 45.6%	(2305.04) 32.0%
Evaluate	(268.13) 7.4%	(136.9) 3.8%	(227.24) 6.3%	(447.36) 6.2%
Individual Work	(0) 0.0%	(5.57) 0.2%	(519.2) 14.4%	(1378.87) 19.2%

The collaboration process actions are shown along the timeline of the sessions in Figure 4. 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 (FTF), the designers worked together during the session. In the baseline study, they spent less time on meta-planning, which occurred at the beginning of the session, and spent more time on the negotiation action. Similar to the baseline study, they spent more time on the negotiation, with some meta-planning actions during the RS session. The remoteness might be the reason for meta-planning-related discussions, when the designers needed to talk about how to manage the design process (issues such as the management of the files/images and time). In contrast to the baseline study, different behaviour patterns are observed in the 3D virtual worlds. The most apparent distinction is having the individual work actions in the 3D and the 3DS sessions. They worked on the separate parts of the design problem and came together for the meta-planning, the negotiation and the evaluation actions, as illustrated in Figure 4. It is also noted that in the 3D virtual 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 3D and the 3DS sessions, and (2) they might be talking about the software features and/or the locations and actions of each other.

Our findings suggest that not only working on paper afforded collaborative activities as reported by Sellen and Harper (2001), but that remote sketching in the digital mode also supported collaborative activities. The results also suggest that 3D virtual worlds encourage individual work as well as supporting the collaborative activities.

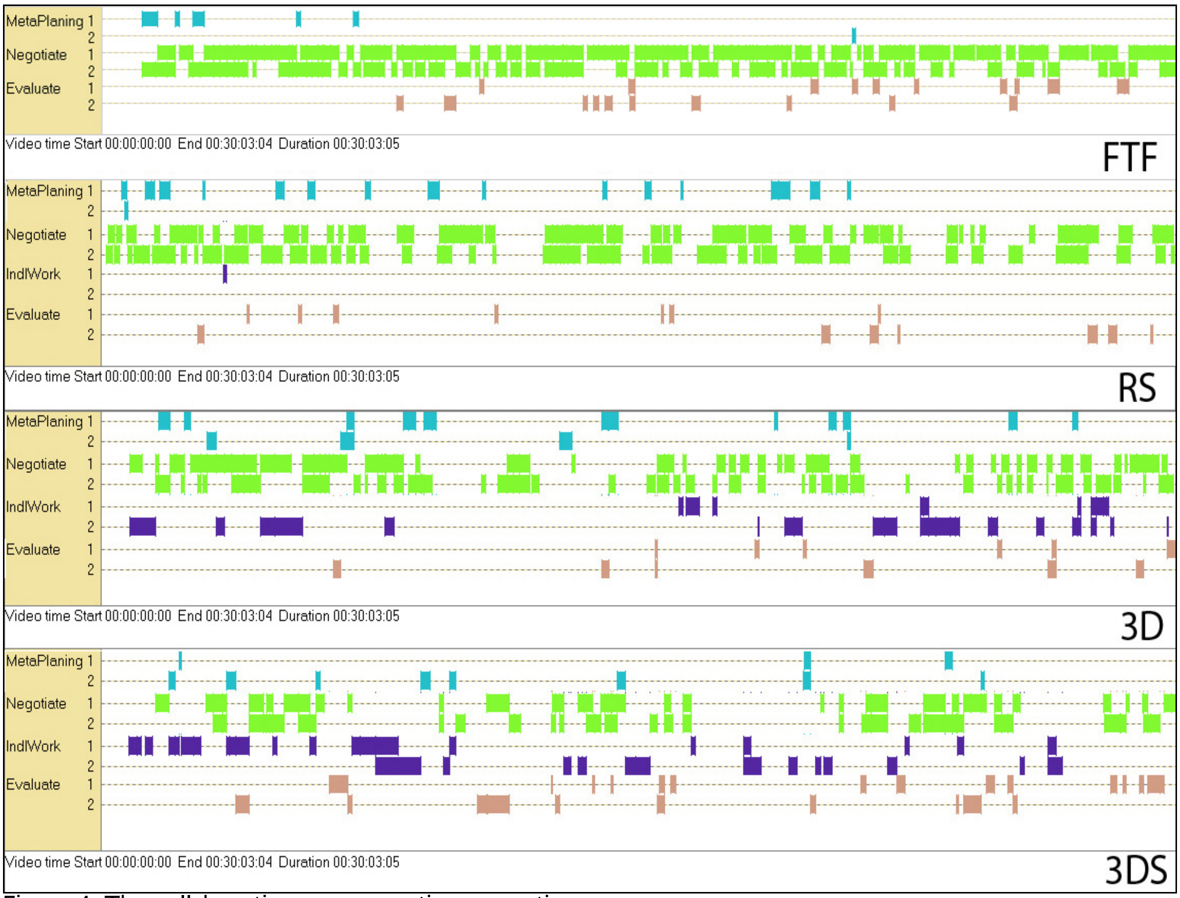


Figure 4: The collaboration process actions over time

Figure 5 shows the duration percentages of the architects' design process actions, comparing the baseline study with the virtual environments. The bar chart shows that the duration percentages of the design process actions are higher in the baseline study (FTF), as shown in Figure 5a. The duration percentages of the solution-moves (proposing ideas) are the highest, followed by the problem analysis, the synthesis, the clarification (ClaRes) and the set-up goal actions in the baseline study. A similar trend with a drop in the overall duration percentages is observed in the RS session, except that there is an increase in the set-up goal actions, as shown in Figure 5. In the 3D and 3DS sessions, there is a drop in the overall duration percentages of the design process actions, compared to the baseline study. In the 3D session, the designers spent time on the analysis of the design problem, followed by the clarification of ideas, the solution-moves, the synthesis and the set-up goal actions. In the 3DS session, the designers spent more time on the set-up goal, followed by the synthesis and the clarification actions, as illustrated in Figure 5 b-c. Although a drop in the duration percentages of the design process actions is observed in the remote environments, a consistent increase in the duration percentages of the set-up goal actions is found when the designers collaborated in virtual environments. The reason for this might be that the remoteness requires the setting-up of goals in terms of managing tasks, monitoring each other's work, and allowing the designers to work separately.

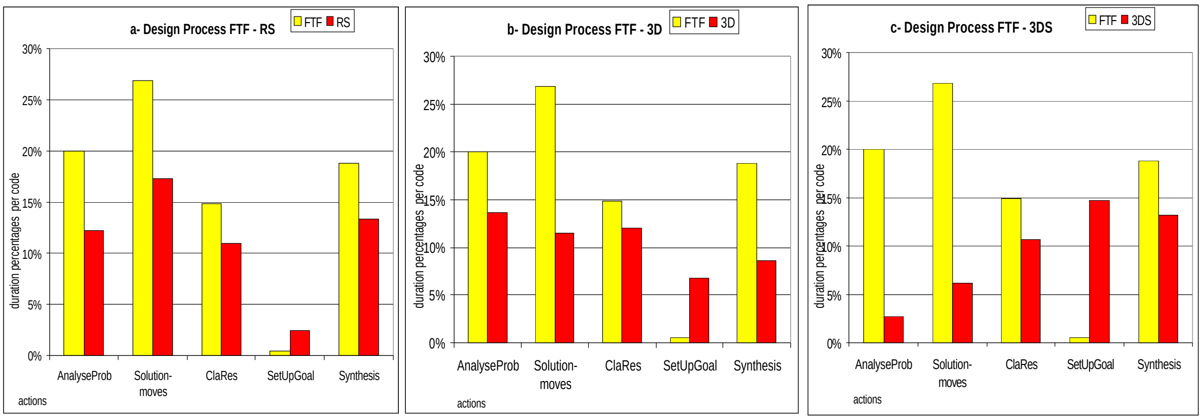


Figure 5: The duration percentages of the design process actions: (a) FTF and RS, (b) FTF and 3D and (c) FTF and 3DS

Figure 6 shows the duration percentages of the design scope actions of the designers, comparing the baseline study with the virtual environments. The graph shows that the designers demonstrated more high-level actions and fewer low-level actions in the baseline study (FTF). The RS session shows a similar trend, as illustrated in Figure 6a. On the other hand, in the 3D and the 3DS sessions, there was an increase in the duration percentages of the low-level scope actions and there was a drop in the high-level scope actions, compared to the baseline study, as shown in Figure 6 b and c. Similar to what has been observed in Vera et al.'s (1998) study, our designers shifted their design exchanges many times in a balanced way, such that high-level and low-level occurred without explicit discussion between participants during the design sessions. This result suggests that sketching encourages designers to stay in a high-level design scope and that 3D modelling promotes elaborating on the design ideas by encouraging the generation of low-level design ideas.

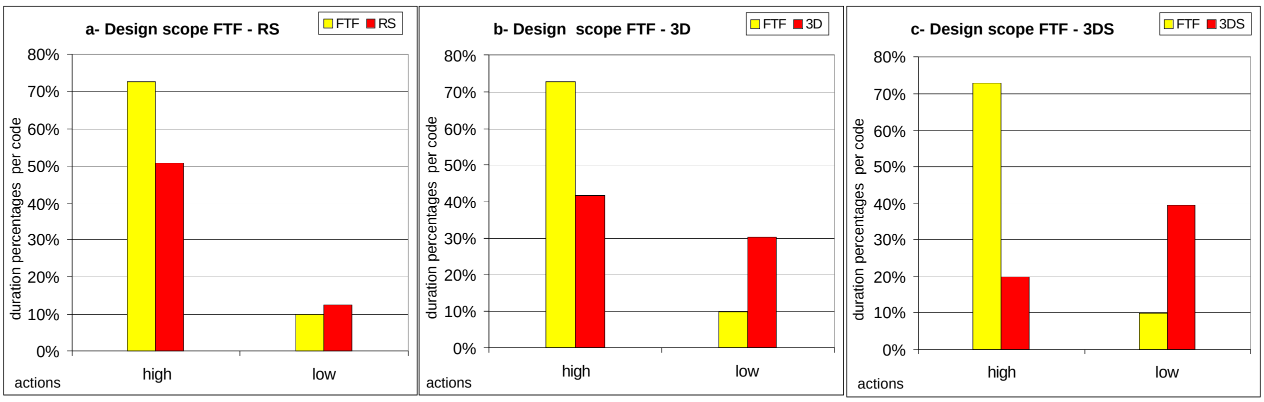


Figure 6: The duration percentages of the design scope actions (a) FTF and RS, (b) FTF and 3D, and (c) FTF and 3DS

- Interaction with External Design Representation Actions

Figure 7 shows the duration percentages of the designers' realisation actions comparing the baseline study (FTF) with the virtual environments. As shown in Figure 7a, in the baseline study, the duration percentages of the 'create' and the 'write' actions are higher, when the designers spent time on writing down the areas and listing the requirements, and drew the design solution. In the RS session, there is an overall increase in the duration percentages of the realisation actions, in that the duration percentages of the create action are higher, compared to the baseline study, as shown in Figure 7a. The 3D and the 3DS sessions show different trends of the realisation actions, compared to the baseline study. The duration percentages of the continue element action is significantly high, followed by the create element and the write action categories in the 3D modelling environments, as shown in Figure 7b and c. This is due to the nature of modelling in 3D 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 a continuing attention on the particular object. That might be one of the reasons for having longer attention spans in the 3D virtual worlds.

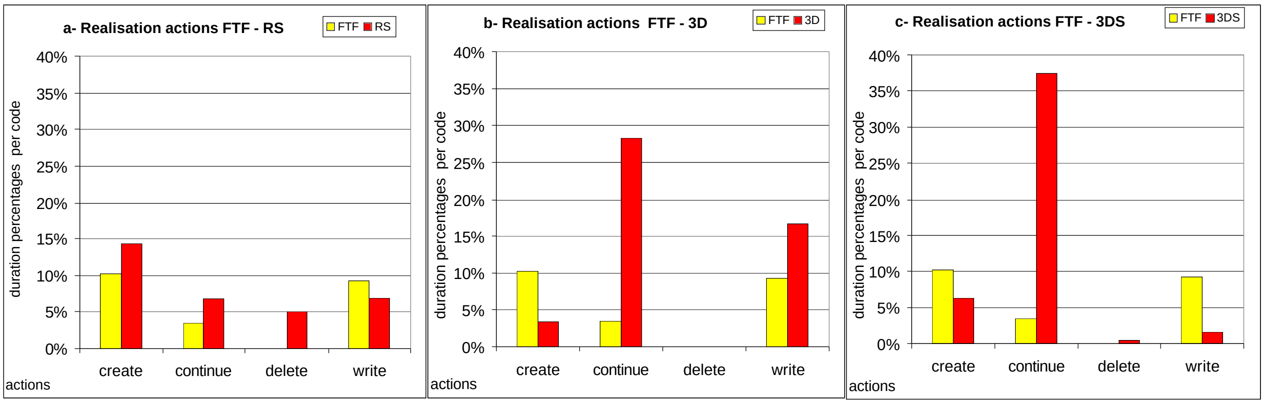


Figure 7: The duration percentages of the realisation actions: (a) FTF and RS, (b) FTF and 3D, and (c) FTF and 3DS

Figure 8 shows the realisation process actions along the timeline of the sessions. In the baseline study, we observed that the designers iterated the realisation process actions (modelling–decision–describing) in smaller chunks during the session, as shown in Figure 8. In the RS session, a similar pattern of the modelling–decision–describing cycle occurred during the design sessions, except that the modelling actions became longer towards the end of the session. The 3D and the 3DS sessions showed a different pattern of behaviour, compared to the baseline study. The iterations of the realisation actions only occurred during the first half of the 3D modelling sessions. Then, for the remaining time, the modelling actions became longer and more frequent, as illustrated in Figure 8. This means that in the baseline study and the RS session, the realisation process actions show the behaviour pattern in which the designers discussed the design ideas/concepts, as well as how to build an idea. In the 3D virtual worlds, the realisation process actions cycle is only observed at the beginning of the session, in which the designers discussed what to do and how to do it. Then for the remaining time, their attention spans remained longer in the making/concretisation of the design ideas, in the 3D virtual worlds.

This is not a surprising result, since studies showed that most participants allocated the greatest percentage of time to the modelling action (Atman and Bursic, 1998; Cardella et al., 2006). What is interesting, however, is that making the design model required longer attention spans on how to build the model (talking about the structure, material, sizes of the elements, etc.) and doing calculations and measurements in 3D modelling. Working on the design representation is a spontaneous activity in co-located sketching. Since the designers are familiar with the use of pen-pencil and sketching, which do not require extra attention, thus the modelling actions become shorter. In the remote virtual environments, the designers were using applications for designing that required certain knowledge and skills to operate. Thus designing activity in remote virtual environments might require extra attention: the detailing of many aspects of the objects such as working on the position and location of the object in the world (x, y, z coordinates), and elaborating on the sizes, shapes, colour and materials.

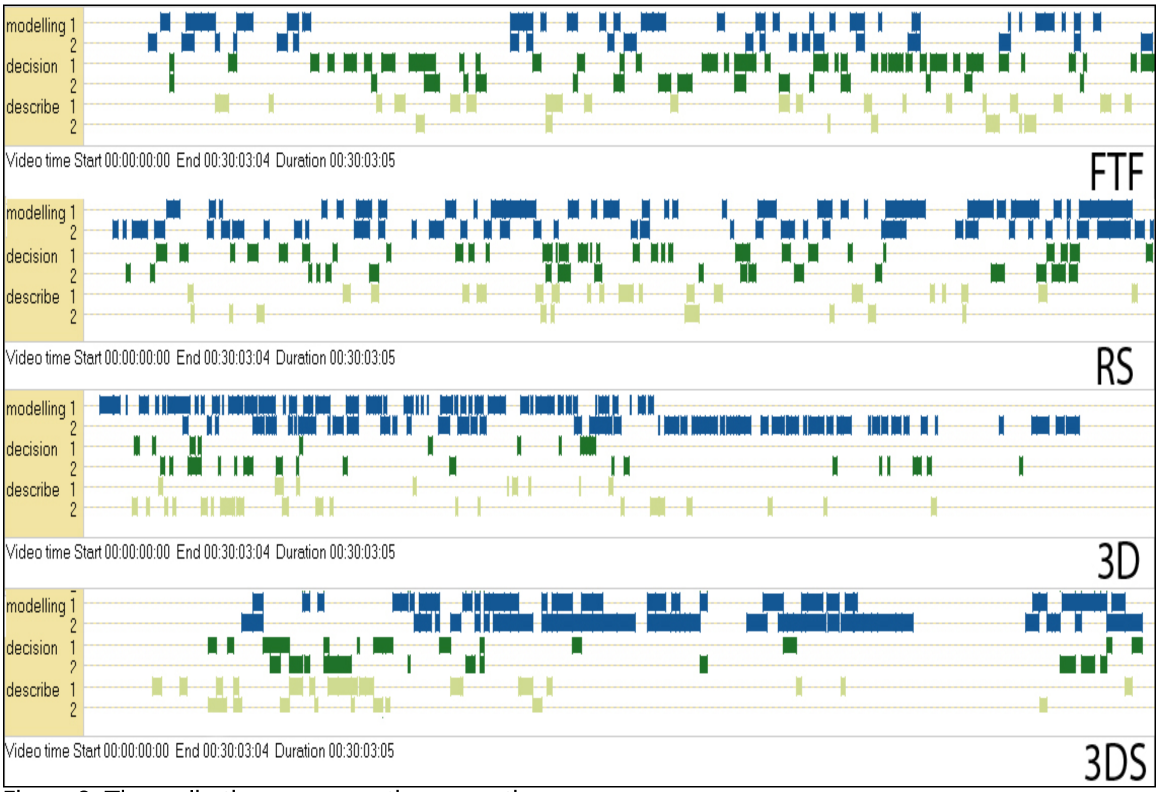


Figure 8: The realisation process actions over time

Figure 9 shows the duration percentages of the perceptual focus actions of the designers comparing the baseline study with the virtual environments. The duration percentages of the object/entity action are higher in the baseline study, as shown in Figure 9a. The RS session shows a similar trend, with a drop in the duration percentages, as shown in Figure 9a. In the 3D and 3DS sessions, there is an increase in the duration percentages of the spatial relationships actions, compared to the baseline study, as illustrated in Figure 9b and c. This shows that (1) the designers focused more on the visual features of the design, 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 3D modelling. The reasons for this difference might be that the 2D and the 3D representations have different properties and they "instil slightly different mental models" (Bryant and Tversky, 1999).

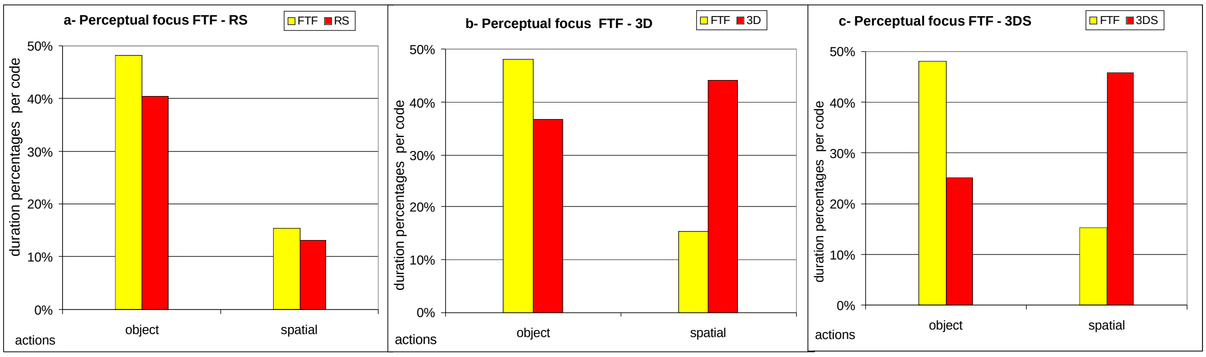


Figure 9: The duration percentages of the perceptual focus actions: (a) FTF and RS, (b) FTF and 3D, and (c) FTF and 3DS

4. CONCLUSIONS

The designers' verbal and visual design protocols have been collected and analysed. The findings of the study indicate that the changes in the design behaviour can be categorised in two different ways: (1) the effect of being in the same location: co-located and remote, and (2) the effect of the type of external representations: sketching and 3D modelling.

First, we found that the design process and the realisation process are different between the co-located sketching and the remote designing. Being in the same location and sketching on paper increased the designers' iterations in the design process actions. Although it is hard to define a pattern on the design process actions, in the co-located sketching the durations of the actions are shorter and more frequent. The designers stayed in the problem-framing, the idea generation and the synthesis of ideas processes, in which their attention shifts changed quickly. In contrast, in the remote designing, the designers had the situation of immediacy to construct the design representation, rather than exploring alternative design solutions. They concretised their design solution without much iteration in the design process actions. They decided on a particular design idea and constructed it, demonstrating longer attention spans.

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

The results of this research imply the followings. First, the use of sketches in design increases collaborative activities more than 3D modelling does. The reason behind the different collaborative activities might be: (1) in the sketching sessions, the designers have the same design representation in front of them, which might encourage them to work together all the time, and (2) in the 3D modelling, the design representation is a shared model but not a shared view, whereby the designers can fly over and walk around the 3D model and they can have a personal view point and workspace. Second, the use of sketches increases the reasoning about the visual features of the design representation and the use of 3D modelling increases the reasoning about the spatial relationships of the design model. The reason for this might be the different properties of sketching and 3D modelling, and the perception of the designer (how they locate themselves within the design representation). 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.

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