

Studying Co-design

How Place and Representation Would Change the Co-design Behavior?

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Abstract. This paper reports the results of a protocol study which explores behavior of designers while they design in pairs using sketching (analogue and remote) and 3D modeling tools (co-located and remote) in co-located and remote locations. The design protocol videos were collected, transcribed, segmented and coded with the customized coding scheme. The coded protocol data was examined to understand the changes of designers' co-design process and their activities of making representation in four different settings. This paper discusses the impact of location and types of representation on collaborative design. The paper concludes that designers were able to adapt their collaboration and design strategies in accordance with the affordability of the used digital environments.

Keywords: Collaborative design · Remote sketching · Augmented reality · Virtual worlds · Protocol analysis

1 Introduction

With the advances in information and communication technologies, developing digital design environments to facilitate collaborative working has become a major research area. Today the construction industry deals with complex design problems that require more knowledge than any single person because the knowledge relevant to a problem is usually distributed among stakeholders [1]. Generating a shared understanding among these stakeholders can facilitate having new insights, new ideas and new artifacts. The shared understanding among collaborators requires working in shared platforms where ideas would be generated, discussed and developed together. Many researchers have studied the developments of shared-virtual design platforms in order to support collaborative activity. For example, the early version of the Augmented Reality (AR) technology in architecture and urban design [2, 3], in design collaboration and management [4], in a mixed reality visualization [5] and sketching in 3D [6, 7] have contributed to the field. In most of those early studies, the technology implementation was usually considered as the tool of representation/documentation for the evaluation of the design idea.

The recent mobile Augmented Reality (AR) and Virtual Reality (VR) technologies have the potential to offer new opportunities to designers as the new co-design

platforms. With those technologies, digital 3D models are generated with the immediacy and accuracy that would be superimposed to physical environment for the visual analysis of the design proposal. Thus, the AR and VR can provide experiences, embodiment and immediate feedback to its users that would not be possible within CAD or traditional design media. Designers can therefore work three-dimensionally since every object within the virtual environment is experienced through movement and interaction. This possibility offers a different ‘conversation’ with their design idea that is otherwise not obvious or possible [8].

The aim of the study is to understand this new conversation with the design idea. We conducted a protocol study with the participation of designers that collaborated across different design medium. Particular focus of the study is on the impact of ‘place’ and ‘types of the representation’ on collaborative design behavior. Having knowledge of similarities and differences of co-design behavior across different digital design medium is thought to be informative for developing innovative collaborative design environments.

2 Studying Design Collaboration

Collaborative designing that resembles the thought processes of individuals is a collective problem solving activity. Researchers argue that the essential elements of design problem solving activity do not change when the expert designers work in groups [9, 10]. Designers’ creative practice can enable collaborative projects to build upon and transcend participants’ expertise and expectations through ‘creative exchange’ [11]. Thus based on the individuals’ expertise on the given design problem, the designer would work intensely in the close-coupled process, or they would work separately in the loose-coupled process. According to Kvan et al. [9], in the close-coupled process, participants work intensely with one another, observing and understanding each other’s moves, the reasoning behind them and the intentions. Furthermore, in the loose-coupled process, the participants work separately on the agreed-upon parts and then they put them together. The participants work together because each has a particular expertise that can contribute to the solution process. Kvan et al. [9] characterized the cognitive model of design collaboration that consists of cyclic joint expert actions (meta-planning, negotiation and evaluation) and separated parallel expert action (individual work), each of short durations.

With the recent developments on the information and communication technologies, collaborative design activity has taken place in computer mediated design environments (CMDEs). The CMDEs will possibly become a common working platform allowing the co-located and remote participations. Researchers argue the possible benefits of the CMDEs’ employment on the workplace, enhancing the perceptual activity [12] and increasing the activities on the information exchanging [13].

In the context of design, the information and design ideas are communicated between co-designers through external design representations such as sketches and models. The act of sketching itself is regarded as important in team design activities in conjunction with having the function of communicating and discussing ideas through sketches [14]. Researchers argue that in synchronous CMDEs, when designers have shared representations and viewpoints, sketching plays an important role providing an

efficient platform for exchanging ideas and collaboration during design process [15]. In the asynchronous context, however, sketching could have adverse effects when incomplete, inaccurate and inconsistent representations do not reflect the original creators' intentions.

Models, however, represent the concretization of design ideas, by getting as close as possible to the actual design intention. Investigating the exterior and interior form, structure, color and lighting would become easy. Models can help within the creative process of visualizing 3D space directly as well as by functioning to help with complex visual relationships, thus models outperform drawings [16]. With the introduction of the digital environments into the design processes, the digital models are considered as new design representations. These have a consistency and a long life span, and do not require continuous reconstruction. This is, in contrast to sketches and physical models, which involve considerable redrawing, tracing and scale-model making [17].

Early research points out that although most digital design systems try to simulate or imitate traditional tools and offer their digital counterparts, the interface of these tools usually affects the 'network' [18]: The 'network' is defined as being between people's mental images, visual perception, hands and representation. The early research also argues that the structured actions with palettes, menus, default values and system messages could break the balance in the 'network', interfering the 'creative flow' [19] and "leading the designers to make decisions prematurely" [20].

In recent years, there are improved systems for conceptual designing with potential to not affect the 'network' and permit the 'creative flow'. This can be only achieved through understanding the design behavior better. Emerging design technologies are encouraging designers to consider new media for effective and efficient collaborative design; the cognitive impact of the emerging technology on designers must therefore be addressed.

3 Proposed Study

Our primary motivation was to design effective digital design environments that would facilitate effective design collaboration. Although the study presented in this chapter focuses on the behavioral change and cognitive impact of digital tools on collaborative design, it is a part of a larger research effort dealing with the development of advanced digital design tools to support co-design activity. Only the result of two pairs of designers' protocol analysis is presented here. The research is funded by The Scientific and Technological Research Council of Turkey (TÜBİTAK) under project number 115K515.

Our initial study consisted of two pairs of designers as they collaborated across four different design environments. Consequently, we setup an empirical study for the purpose of gaining deeper understanding of the changes on the designers' collaboration and their interaction within the given environments. The assumption of the study was that a comparison of the same designers in four different environments would provide better indication of the impact of the environments than using different designers and the same design task (similar to the earlier studies [21]). With these ideas in mind, a study with four different settings was developed, as indicated in the Table 1: (1) face-to-face analogue sketching (F2F), (2) remote sketching (RS), (3) co-located 3D modeling with marker-based mobile AR application (MAR), and (4) remote 3D modeling in a Virtual

Table 1. Research matrix, location and representation.

Research matrix		Locations	
		Co-located	Remote
Representations	Sketching	Face to face sketching (F2F)	Remote sketching (RS)
	3D modeling	Co-located modeling with marker-based mobile Augmented Reality tool (MAR)	Remote 3D modeling in Virtual World (VW)

World (VW). The below section explains the experiment apparatus and the environments.

3.1 Experiment Apparatus and Set-Up

Two pairs of architects participated in the study. They were given the consent of participation and some training information about the digital platforms prior to the experiments. Then, they were provided with four different design briefs with similar difficulty and were asked to come up with schematic design solutions in 30 min in each of the design settings. In the design briefs, the participants were asked to consider the

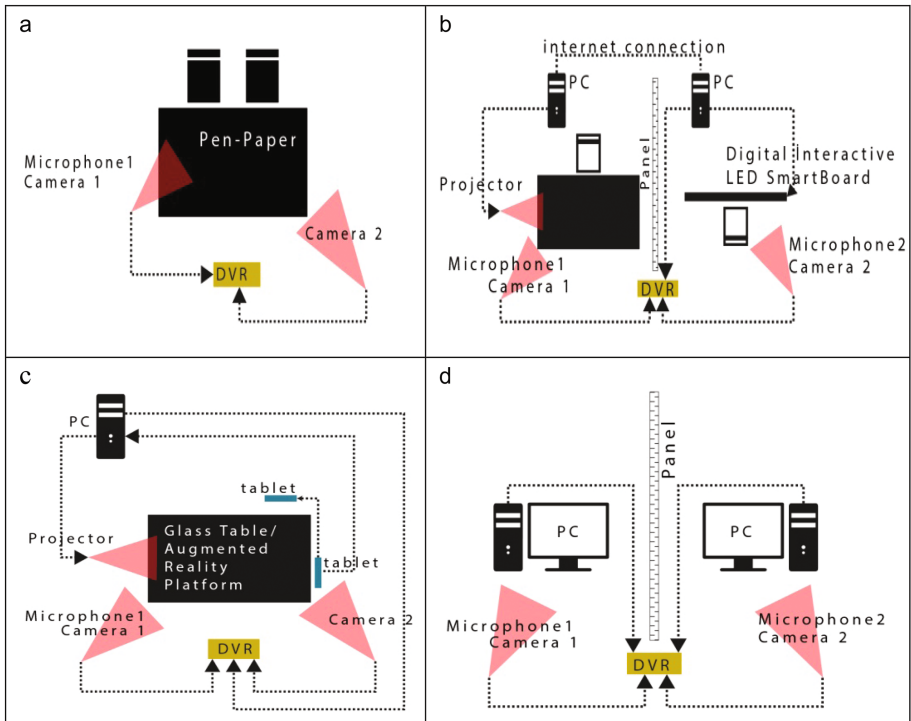


Fig. 1. Experiment apparatus and set-up for the phases

climate of the region, the context of the surrounding and the relation with its neighbors. In terms of the context of design, they were expected to consider open, semi-open and closed spaces for different public functions. Figure 1 shows the overall set-up of the experiments: (a) the first setting shown in Fig. 1a was the face-to-face sketching (F2F), (b) the second phase was the remote sketching (RS) as shown in Fig. 1b, (c) the third phase that was the co-located 3D modeling with mobile augmented reality tool (MAR) is shown in Fig. 1c, and (d) the final phase, shown in Fig. 1d, was the remote 3D modeling in a virtual world (VW). To simulate high bandwidth Internet connection, the participants were in the same room separated with a panel between them, as shown in Fig. 1. Camera views, screen views and a microphone were connected to a Digital Video Recoding (DVR) system that was used to capture the collaborating participants' actions and communications in all sessions.

Phase 1: Face-to-face analogue sketching (F2F). The first design environment is the co-located face-to-face analogue sketching. Two designers were given analogue tools (pen and paper, rules etc.) during the design process. Figure 1a shows the experimental set-up of the F2F phase, in which two architects were working together around a table. Figure 2 shows that two participants were working together around a table (on the left), and the view of some of their sketches (on the right).

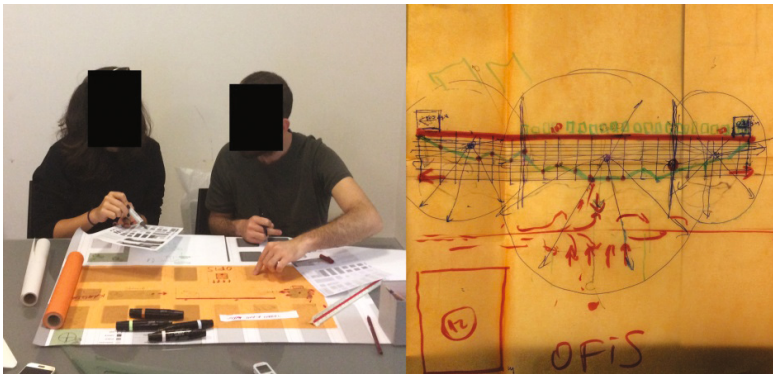


Fig. 2. Two participants working together and an example of the outcome from the Phase 1.

Phase 2: Remote (digital) sketching (RS). In this phase, the designers used a web-based shared whiteboard application that provides lines, text, form, color, editing etc. and a text-based communication channel (Groupboard). To simulate the high bandwidth communication, the participants were in the same room, but could not see each other, as shown in Fig. 1b. One of the participants used a customized glass-top table with the digital pen tool (MimioTech) with the view projected under (the view of the computer screen was projected out under the glass table), as shown in Fig. 3. The other designer used a digital pen on wide-screen (Wacom) tablet.

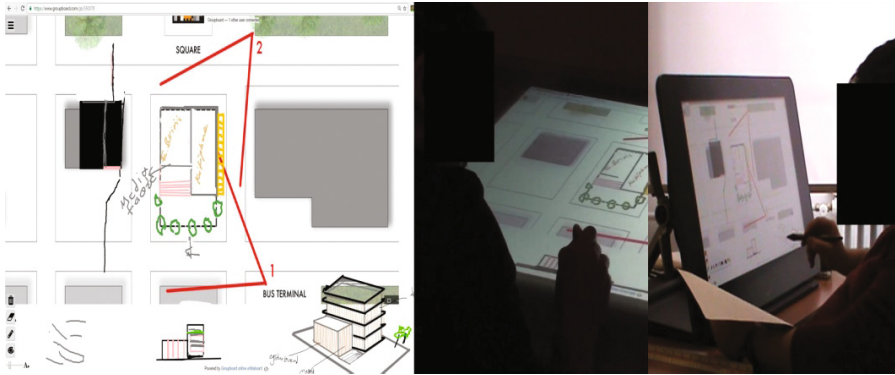


Fig. 3. The screen shot of the shared whiteboard application and views from the Phase 2.

Phase 3: Co-located 3D modeling with a Marker-based Augmented Reality Tool (MAR). In the third phase, the co-located 3D modeling, designers were given two 9' tablets with the MAR, several markers and an enhanced design environment that consists of the physical model of the site in 1:500 scale, and the shared view of one of the tablets is projected under the glass-top table, as shown in Fig. 4.



Fig. 4. The interface of the developed MAR tool and a view from the phase 3.

MAR: The Marker-Based Mobile Augmented Reality Tool. An AR application was developed using the Unity 3D game engine with the Vuforia AR plug-in that offers the set of target objects' library, object recognition and extended tracking (see [22], for the details of the system). First, a set of marker images was defined in the Vuforia AR library, and then the data set of the image targets was uploaded in the Unity 3D platform. The image targets were the unique predefined 2D shapes, similar to the QR codes, which were recognized by the device's camera. In the Unity 3D platform, the data set of the image markers was set to correspond with the primitive geometric objects (cube, sphere and cylinder) that would be the design elements for the phase 3.

The interaction with the tablet screen achieved a direct manipulation of the design elements. Several scripts were written to allow manipulations as follows: scaling the objects on the x, y, z directions, changing the location of the object on the x-y plane and z direction, rotating the object on the x, y, z polar coordinates, and changing the color of the objects. In addition, the reset, save and activate options were implemented on the interface, as shown in Fig. 4.

One of the tablet screens was shared through a mirroring application, thus both participants were able to create and modify the objects on the scene. In addition, a large shared display was provided on the glass-top table and a model of the context to provide an enhanced design environment, as illustrated in Fig. 4.

Phase 4: Remote 3D modeling in a Virtual World (VW). In the last phase, designers used a collaborative 3D VW, Second Life. For this phase, designers were given 24'-wide screen desktops. Second Life (SL) is a multi-user collaborative VW with the object-based 3D modeling capabilities that consists of a library of the basic geometries (cube, sphere and cylinder etc.) and wide range of editing tools. In SL, an island – VirtualStudioITU-, with some buildings are already on it, provided as a context for the designers to work on, as shown in Fig. 5. Similar to the other remote design phase, we put a panel between the participants to simulate the high-bandwidth communication.

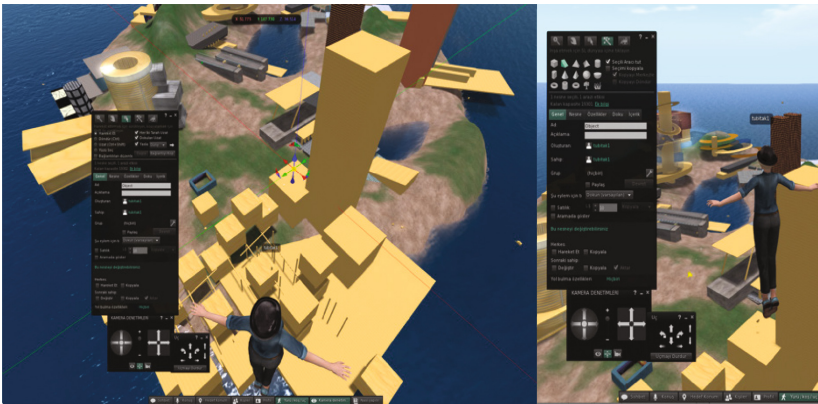


Fig. 5. Screen shots of the VirtualStudioITU, showing the edit and build menus of SL

Following the collection of the designers' actions and verbal expressions, a thorough investigation has taken place using the protocol analysis method.

4 Methodology

Since the early studies of Watson where the verbalization is at the core of thinking [23], 'researchers have primarily relied on verbal behavior as a significant trace of the cognitive activities mediating between stimulus and response' (as indicated in [24]) This understanding has been applied to study cognitive activities on several

design-related fields. For example, in the engineering domain, protocol analysis is a well-documented approach to understand what a participant is thinking while solving a problem [25]. Later, studies acknowledge the importance of external representations and drawings that are associated with the design thinking which can be interpreted through verbal expressions [26, 27].

In collaborative design studies, unlike the think-aloud and retrospective protocols, the design dialogues are the context of the analysis. We are adopting a Vygotskian [28] view on the relationship between thought and speech, as discussed in detail in [29]. Thus, in the area of design collaboration, studies contemplate that communicating with others has been seen as similar reflections of cognitive processes [29, 30]. We reflect on the teams' design protocols that resemble the 'think aloud' method, since the design dialogues during a joint task have potentials to offer data that is indicative of the cognitive abilities of the team members. The analysis of the design protocol is a complex process that includes collecting, indexing, structuring large video data and investigating the relationships and the patterns of designers' behavior, explained as follows.

4.1 Segmentation

The transcription of the data is the first step, and then there is the segmentation phase that means dividing the design protocols into smaller units. In collaborative design studies, the data contains a large continuous stream of dialogues and video recordings. Since we aim to understand the role of the place and representations on collaborative design, a thorough investigation of designers' communication and the activities on the external design representation has to be done. A hybrid method was used for the segmentation of the protocols based on two sources: (1) Gero and McNeill [31]'s definition: 'flag the changes in actions and intentions', (2) Maher et al.'s [21] definition: 'flag when there is a change in the 'who' and 'what' items. The next step was to assign a code for each of the segments in order to measure the changes of the designers' cognitive activities.

4.2 Coding Scheme

Following the segmentation of the design protocols, we examined the activities using a coding scheme, as shown in Table 2. The basis for the development of the coding scheme was the expected results of the study that 'types of presentation and location would have an impact on co-designers behavior'. Thus measuring the changes in activities of (1) the co-designing and (2) the representation-making were essential. Table 2 shows the classes, the related codes for each class and the descriptions of the codes.

Table 2. Coding scheme.

Classes	Codes	Descriptions
Co-design model* [9]	Meta-planning	Planning the design process
	Negotiation	Talking about an issue or an aspect of design
	Evaluate	Determination of the values of design proposals.
	Individual work	Team members are working alone
Realization action [10]	Write	Typing about aspects of design
	Create	Generating a visual proposal for the first time
	Continue	Continue modeling with created proposal
	Delete	Erasing a part of generated proposal
Realization process* [10]	Decision	Agreement on a proposal
	Describe	Explaining an issue or an aspect of design
	Modeling	Discussing on making a representation (model – sketch)
Design process*	Analyze	Examining an issue of a design proposal
	Propose	Stating a new idea about the design
	Setup goals	Planning for achieving a goal
	Synthesize	Reaching a result by combining analyzes
	Evaluate	Determination of the values of design proposals.
Design space*	3D	Modeling action in three dimensional space
	2D	Modeling action in two dimensional space
Collaboration mode	Individual	Team members are working alone
	Team	Working collaboratively
Shared content	On given model	Working with given information about design task
	On proposal	Working on design proposal
Design exchange* [32]	High level	Dealing with general concepts of design task
	Low level	Dealing with details of design task

*Classes are determined by the investigation of the verbal expressions only.

4.3 Coding Process and Data Analysis

Two researchers coded the segments separately (see [25], for more on the coding process) which includes validating the segments in arithmetic order by listening-viewing the audio-video recorded data as well as reading the transcripts of the segments. Based on the researcher's understanding of the segments and the coding scheme, each segment was assigned with a code from the above scheme. After both researchers finished the individual coding, they combined their results in a joint arbitration process, as described in [33].

The occurrence frequency of each classes and codes (see Table 2) was investigated with the behavior analysis software, INTERACT 15. The software gave us information about the specific time interval indicating the changes in the co-design activity, see [34] for the details of the supporting software.

5 Results

This section presents the empirical evidence for the changes of the designers' co-design activities when they use digital tools. To measure the similarities and differences of designers' activities in each of the design sessions, the duration percentages of each class and codes were calculated within each environment. To examine the changes caused by the design environments, the pattern of behavior was also explored visually through the timeline graphs, as follows.

The shift of attention was examined by an analysis of the segment durations in each session, as shown in Table 3. Since a continuous stream of video data was segmented based on the hybrid method, the segment numbers and durations provide us with the information about how frequently the changes/shifts occurred. The biggest segment number is observed in the F2F phase for both pairs (199–166), the smallest segment number is observed in the VW phase for both pairs (151–131), as shown in Table 3. The most frequently occurring segment durations are smaller in both sketching environments: F2F (4.52–2.76) and RS (4.77–3.91) and are higher in both 3D modeling environments: MAR (5.41–6.05) and VW (6.04–7.04), as shown in the mode durations below. The mode values and maximum segment durations increase when the virtuality is introduced to the design activity, comparing F2F-RS and MAR-VW. The similar increase on the standard deviation values is also shown this tendency. The segment durations for all sessions are positively skewed. The high kurtosis values show that the distribution of the durations of segments is not flat. The distribution of the segment durations along the segment numbers in the design phases is shown in Fig. 6. The timeline also shows that the segment durations are longer in both 3D modeling environments (MAR and VW).

Table 3. Statistics on the duration of segments.

Segments	Co-locate		Remote		Co-locate		Remote	
	Sketching				3D modeling			
	F2F		RS		MAR		VW	
(second)	<i>Pair 1</i>	<i>Pair 2</i>	<i>Pair 1</i>	<i>Pair 2</i>	<i>Pair 1</i>	<i>Pair 2</i>	<i>Pair 1</i>	<i>Pair 2</i>
Median	7.37	6.56	7.16	7.36	7.6	8.56	7.73	7.66
Mode	4.52	2.76	4.77	3.91	5.41	6.05	6.04	7.04
Max	47.82	81.01	57.24	82.98	70.95	83.54	75.91	92.23
Min	1.33	0.98	0.86	1.21	1.14	1.25	1.03	1.04
Skewness	2.40	3.90	2.70	3.18	3.15	2.49	2.35	2.74
Kurtosis	8.16	13.07	11.26	12.77	14.86	8.07	6.57	7.97
Stan.Dev.	7.18	11.96	7.43	12.36	10.21	12.47	12.80	16.97
Segm.Num	199	166	197	162	172	144	151	131

Overview of the Classes. The duration percentages of the classes are shown, in Fig. 7. The duration of each class is divided by the total elapsed time for each design session (within each phase - 30 min), and then the average duration percentage is determined.

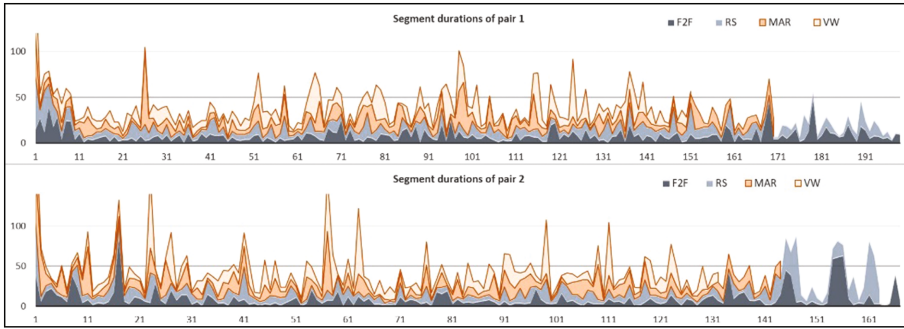


Fig. 6. The distribution of the segment durations

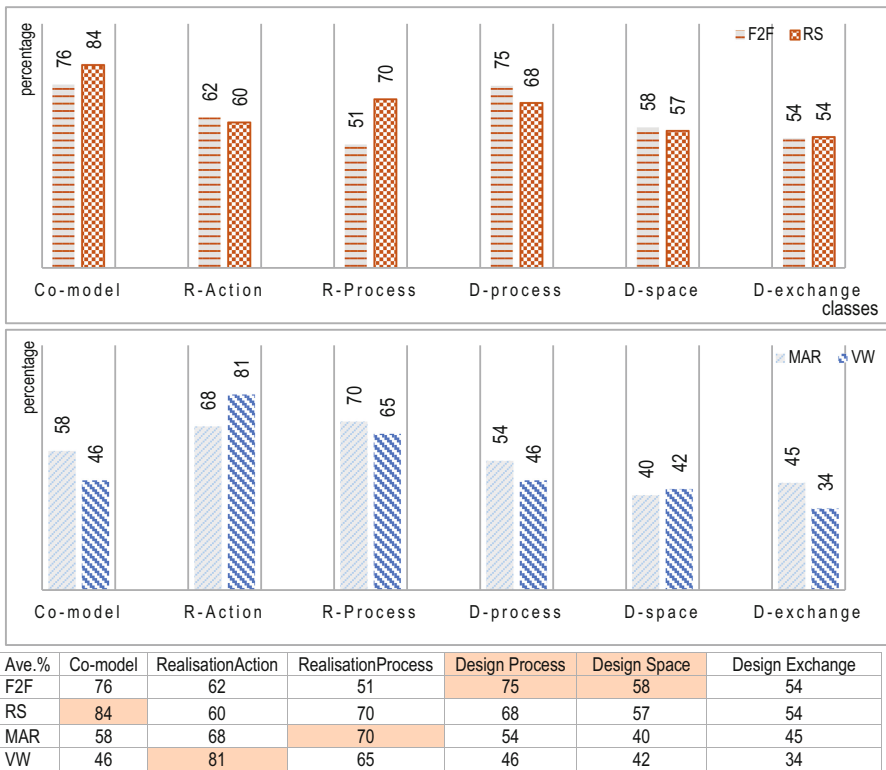


Fig. 7. Average duration percentages of overall classes

First, we examine the overall durations of each class: The duration percentage of the design process class is higher in the F2F (75%) session (that are determined from the verbal expressions), followed by a drop in remote sketching and both 3D modeling environments (MAR and VW). The classes are the co-modeling (76% in F2F – 84% in

RS and 58% in MAR – 46% in VW), the design process (75% in F2F – 68% in RS and 54% in MAR – 46% in VW), the design space (58% in F2F – 57% in RS and 40% in MAR – 42% in VW), and the design exchange (54% in F2F – 54% in RS and 45% in MAR – 34% in VW) classes, as shown in the Fig. 7.

Only the duration percentages of the realization classes are higher in the 3D modeling environments: the realization process (51% in F2F – 70% in RS and 70% in MAR – 65% in VW) and the realization actions (62% in F2F – 60% in RS and 68% in MAR – 81% in VW). The ‘realization process’ class represents the verbal expressions that are related to the making of the design representation in the given setting, explaining how to make the model, describing what the objects on the scene would mean etc. The discussions about making the model increase in the 3D modeling environments and the highest duration percentage of the realization actions (create-continue-delete-write actions- that are determined from the video data) is seen in the VW session (81%). Those finding were investigated further below.

5.1 Design Process

We report the results of the analysis of the comparison across different place, co-located versus remote (F2F vs RS and MAR vs VW): Only the duration percentages of the design process class (75% in F2F vs 68% in RS and 54% in MAR vs 46% in VW) is higher in the co-located phases, as shown above in Fig. 7. Thus, we investigate the design process class in detail; the duration percentages for each code within each phase is plotted on the same chart for the comparison, as shown in Fig. 8. The highest duration occurs in ‘propose’ in both sketching phases, followed by the MAR (16%) and the VW (14%) phases. The durations of ‘analyze’ and ‘synthesize’ codes are also higher in the F2F, followed by the RS, the MAR and the VW phases, as shown in Fig. 8. The higher duration of ‘set-up goal’ occurs in the remote locations, 9% in the VW, followed by the RS (6%), as shown in Fig. 8. Most ‘evaluation’ code occurs in the RS phase, followed by the MAR, the F2F and the VW phases.

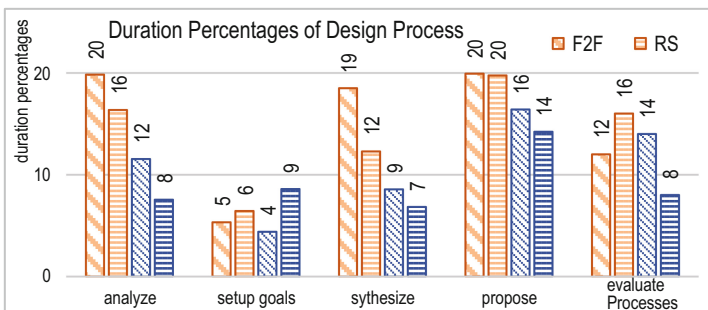


Fig. 8. The average duration percentages of the design process class in all sessions

5.2 Realization Actions

We report the results of the analysis of the realization activities comparing across two media: sketching versus 3D modeling: (F2F - RS vs MAR - VW): the overall duration percentages of the realization action are higher in both 3D modeling environments, as shown above in Fig. 7. Thus, we further investigate this class that is determined through the investigation of the video data, as shown in Fig. 9. The realization action class represents the interaction with the design representation that is related to the making activities including creating and modifying the external design representation (sketches and models) see [15] for more details). The duration percentage of ‘continue’ action (includes all kinds of modifying/editing activities) is higher in the 3D modeling phases: the VW (74%) phase is the highest, followed by the MAR (52%), the F2F (31%) and the RS (18%). The duration of create action is higher in the RS (32%), followed by the F2F (26%), the MAR (11%) and the VW (5%). The write and delete activities occur for a short period of time, as shown in Fig. 9.

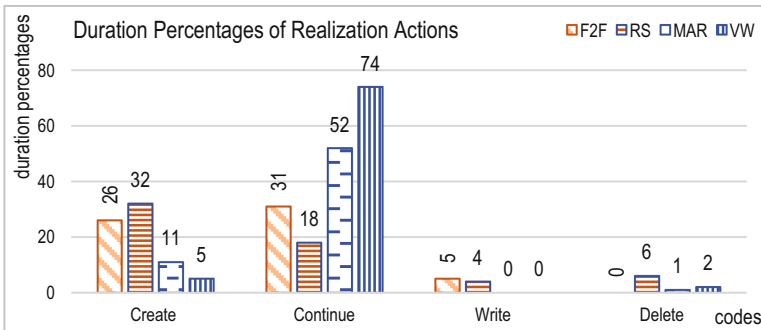


Fig. 9. The average duration percentages of the realization action class

5.3 Co-design Model

The duration of the co-design model class is investigated as shown in Fig. 10. This analysis shows the average durations of the co-design model class over time in all design phases. In the RS phase, the duration percentages of the ‘negotiate’ and ‘evaluate’ actions are higher. An overall drop is observed in the 3D modeling phases, except the ‘meta-planning’ and ‘individual-work’ is slightly higher in the remote 3D modeling phase (VW). As discussed later, several features of SL had an impact on this. Based on the verbal design protocols, closed-coupled and loosed-coupled working models, as suggested by [9] iterated in all of the design sessions with a different pattern. This result also confirms previous design studies [9, 10] that show designers work on their collaborative design tasks using the same collaborative process with less iterations (meta-planning, negotiation, individual work and evaluation) regardless of the technology change. This finding also confirms that ‘designers adapt the nature of their communication to the bandwidth of the channel available without compromising their collaborative strategy or expert contributions’ [35].

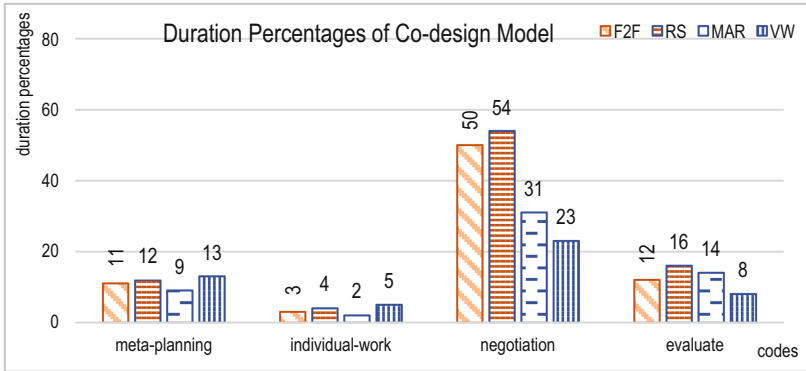


Fig. 10. The average duration percentages of the co-design model class

To investigate this model further, the classes of the ‘co-design model’ and the ‘realization activity’ are plotted along the timeline of the phases, as shown in Fig. 11. Each horizontal bar indicates the durations of each operations; the beginning is on the left whereas the end is on the right. Figure 11 shows the co-design model class along the timeline of the phases; the pattern of the model starts with the meta-planning activity in all phases, continued with the ‘negotiation’ action in longer time segments, followed by the ‘individual-work’ action and shorter ‘evaluation’. There are some long empty time slots as indicated with the dotted lines in the 3D modeling phases, as shown in Fig. 11. This happened when designers are not articulating and expressing their thoughts verbally, instead their attention shifted to the making of the 3D model. Thus, we plotted the class of realization activity onto the same timeline, as shown in Fig. 11.

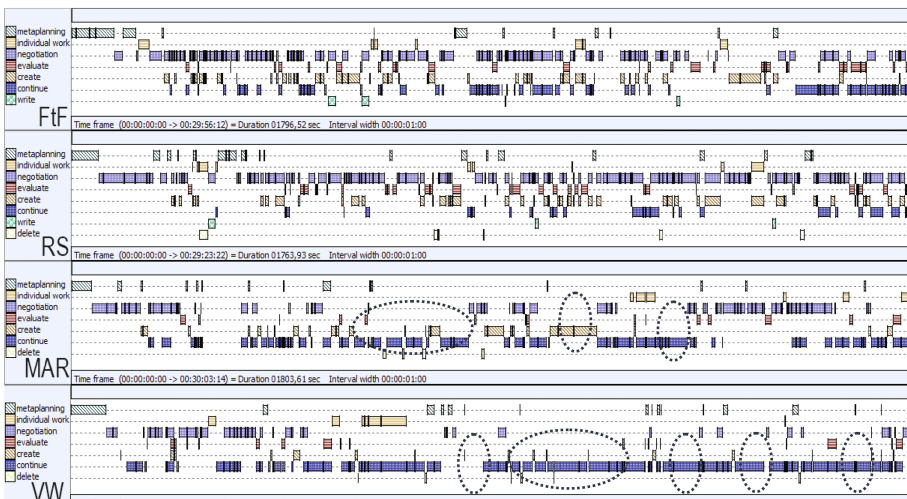


Fig. 11. Timeline of parallel actions – co-design model and realization activities

The ‘create’ and ‘continue’ activities are synchronous with the design and collaboration process (having verbal expressions) in both sketching, but they become separated in both 3D modeling environment, as shown in the timeline.

6 Discussions

The findings of the shifts of attention suggest that the designers had more new actions and shifted them quickly in the co-located phases (less time – more segments). But they spent more time on an action before they engaged in a new action demonstrating less and longer shifts of attention in the remote locations; when comparing F2F versus RS and MAR versus VW sessions. This consistent finding suggest that the remoteness and technology inclusion in the collaborative design activity would have an impact on the designers’ cognitive load in a certain degree as designers had to pursue each action in more detail in the remote digital design environments.

During the design sessions, we observe that designers were able to adapt their collaboration and design strategies in relation with the affordability of the given digital environment. The appropriation that is ‘the process by which people adopt and adapt technologies, fitting them into their working practices’ [36] demonstrating similar semantic ‘(change in meaning or significance of the technology in context) and behavioral (novel usage patterns)’ [37] adaptation. We advocate that the affordances of the tools and interface contribute the developing of the ‘appropriation’ by demonstrating new design behavior. This appropriation generates a transformation of the attention of designers’ on the specific design aspect in relation to the features of the employed design tool.

The findings of the realization class suggest that both sketching environments (whether or not technology is involved) encourage designers to communicate about the development of the design concept more than the 3D modeling environments do. The verbal externalizations of thoughts occurred less in both 3D modeling phases. Thus, the intensity of the verbal expressions about the design concept drops and the shifts of designers’ attention to modeling and examining the visual appearance of the design proposal increase in the 3D modeling phases. In particular, in the VW, the key topic of the discussions is mainly on the making of the design model, how it looks from different view-points, the visuo-spatial relationship of the design elements and the visual evaluation of the appearance of the design proposal within the given context. This particular finding replicates the research on collaborative design in VW [15]; [38] where the participants allocated greatest percentage of time to the modeling action. In the MAR environment, the focus of designers’ is on the ‘representational semantic’ of the design objects on the scene. That means that the designers have to identify and to assign new functional and programmatic narratives to the objects on the scene as a kind of tagging. For example, the yellow box is for the museum, the long blue sphere is the gathering space, etc. That might have happened because the interface allows for working on basic geometries that facilitate a massing study.

Sketches are representations of visual thoughts that help the facilitation of the perception and conveying of the ideas in a collaborative design setting. Thus, the rise of the design process related discussions on analogue sketching and the drop on the communication about design development in the remote digital environments (the drop

of the duration percentages of the ‘analyze’, ‘synthesize’ and ‘propose’ codes) are not surprising. However, the evaluation of the design proposal and the set-up goal activities do not follow this trend. We speculate that since being in remote places requires an additional attention on monitoring and managing collaborative activities, designers thus assigned roles to each other in the remote digital environments. In particular, in the VW phase, the design objects shared in SL that encourages designers to allocate some tasks to each other for modifying the model. For example, one designer stood on top of the design model while the other designer inspected and instructed what to do with the model in SL. Similarly, the shared whiteboard on the remote sketching phase encourages the designers to work together facilitating the closed-coupled process (92% team mode), thus designers tend to confirm every design decision to proceed. Thus, the duration percentages of the evaluation code become higher in the remote sketching phase. Similarly, the MAR phase also includes the shared view of the tablets and provides the shared operations on the design objects. The sharing of the working environment encourages designers to work in the close-coupled process. This finding confirms that the affordability of the interface had an impact on the collaboration process, as indicated by [12]: ‘the dense collaborative actions is said to be that the user interface helps the designers to get focus on the different aspects of design which make designers work much more engaged in the process of conceptual design’. Thus, to proceed further for the design development, designers need to evaluate every step of their decisions in the close-coupled mode in the shared environments.

The time spent on the realization of the design representations (including activities related to the making of the model) are longer in the 3D modeling environments. This is due to the nature of the modeling, in the 3D design environments: In SL, one mouse click creates the basic objects on the scene (cube, pyramid, tetrahedron, torus, sphere, cone, tube, cylinder, ring, tree and grass objects etc.) and then, designer needs to manipulate the objects’ properties to make other things. During these manipulations, designer would inspect the objects’ form in different viewpoints to determine a satisfactory result. Thus, making the 3D model in the SL is a constant modeling activity. This is consistent with a cycle of actions such as move/rotate/transfer/group etc. as pointed out by [39]. In order to have a desired building form, designers need to modify the objects by rotating, moving, scaling and changing color, mapping a texture onto it in the VW. Similarly, in the MAR environment, creating a basic object requires displaying a marker to the tablets’ camera. Then, the object becomes registered in the system. Then, designer needs to modify the properties of the object to make other things. Thus longer ‘continue’ action that consists of series of actions requiring a continuing attention on the objects occurs in the 3D modeling environments. During the ‘continue’ operation, designers also examine the visual appearance of the artifact by zoom in /zoom out and orbiting the view in the SL. In the MAR, the visual examination takes place on the tablets’ view through the bodily engagements of the designers by bending their knees, moving up and down the tablet to catch the best scene. Thus, investigating the visuo-spatial properties of the design artifact becomes a major activity in both 3D modeling environments. That is one of the reasons for having ‘longer spans of attention’ in the 3D modeling environments as well (see Fig. 6).

The plot of the parallel actions on the same timeline suggests that the articulation of design concepts and the developing (making) of design representations are simultaneous

collaborative activities in sketching, but they become separated actions in the 3D modeling environments. The externalization of thoughts occurs less in 3D modeling. The loosely-coupled process is mostly observed in the VW, as designers make task allocations to then separate and do their individual modeling tasks. In the MAR environment, on the other hand, they operate the ‘continue’ action in the close-coupled process, but mostly in a silent mode.

7 Conclusions and Future Remarks

This paper presents the results of a protocol study based on an experiment with pairs of designers working across different design settings. From the protocol analysis, co-designers’ activities, their interactions with representations and with the interfaces of the tools have been explored. Results of this study suggest that collaborative designers are able to adopt and adapt technologies in order to achieve satisfactory design solutions. The results indicate that co-designers illustrate behavioral adaptation based on the affordances of the used technology. Each digital design environment provides different experiences of co-design behavior and contextual interaction.

The alchemy of design collaborations across the digital media shows that designers are able to design successfully in all the examined environments generating a design outcome, addressing the briefs. The properties of the environments that are the interfaces and tools, the field of view, sharing of the virtual space have great impact on the collaborative activities and on the behaviors of the designers. The cyclic co-design processes of collaboration with different intensity were occurred across the digital media. In particular, ‘what you see is what I see’ kind of shared environments support the close-coupled collaboration processes in which designers tend to achieve the consensus of decisions to proceed further. The shared environments where users have their own field of views and options to navigate alone encourage designers to work in the loosely-coupled collaboration process.

Regardless of the involvement of the technology, sketching provides designers a shared platform where they simultaneously generate design ideas and develop the design representations. In the 3D modeling, the model making and the generation of the design ideas become separated activities. In the co-located 3D modeling environment, the broken ‘network’ between the virtual and physical has been an impact on the process of idea generation, but superimposing the virtual model on the physical model gives them the opportunities to examine and develop the perceptual aspects of the design proposal. The VW with the detailed and complex modeling possibilities and having realistic looking context gives designers the possibilities to articulate the design artifact in more detail.

In conclusion, a design interface which is highly isolated from the interactions in physical reality can generate occlusions in the processes of idea generation. The physical reality context can be a prompting or impeding factor in the design cognition through the processes of idea generation. Thus, the benefits or impacts of superimposing the virtual and the real on the design context which can be provided by the augmented reality environments requires further study.

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